The glacial geomorphology of the Firth of Forth

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Abstract

It is important to understand how past ice sheets both responded to and perturbed the ocean-climate system in order to help predict how current ice sheets will respond to future changes and, in particular, warming of the atmosphere and oceans. Ice streams are an important component of ice sheet dynamics and are a mechanism through which ice sheets can rapidly lose mass in response to external forcing. The British Irish Ice Sheet (BIIS) is thought to be a valuable analogue for future changes in ice sheets and has been extensively studied. Several palaeo-ice streams have been identified, but the inventory of palaeo-ice streams is unlikely to be complete. This thesis is aimed at identifying the likelihood of palaeo-ice streaming in the Firth of Forth region, south-east Scotland, where previous work and numerical modelling has hypothesised ice stream activity. However, and perhaps surprisingly, the glacial geomorphological evidence for ice stream has not yet been studied in detail. In this study, the glacial geomorphology of the Forth region has been examined and characterised using remote sensing imagery from the NEXTMap digital elevation model. Over 10,000 individual landforms have been identified, categorised and manually digitised in to a Geographic Information System (GIS). Established criteria has been used to test whether the Firth of Forth was the location of an ice stream and the subglacial landsystem has been examined to determine the relative roles of bedrock geology and topography. Both soft and hard bed signatures have been considered when analysing the subglacial landsystem, which is shown to be highly complex. The chronology and glacial history of the Forth has then been reconstructed using available dates in the

area and through analysis and consideration of the subglacial landform and landsystems identified. The influence of the Forth region on regional ice sheet history has also been considered. Results reveal five different types of landform; flow traces, drumlins, intermediate forms, crag-and-tails and streamlined bedrock ridges. However, it is argued that they lie along a continuum that reflects the influence of underlying bedrock geology and drift thickness. It is concluded that the diverse collection of landforms identified indicates that the Forth imprint represents a mixed bed onset zone of a palaeo-ice stream that extended offshore and operated around 19 ka – 15 ka. This paper is the first to present evidence and formally identify the Forth area as a palaeo-ice stream, which was the largest terrestrial onshore imprint of a palaeo-ice stream identified on the east coast of the BIIS.

The glacial geomorphology of the Firth of Forth

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I confirm that no part of the material presented in this thesis has previously been submitted by me or any other person for a degree in this or any other university. In all cases, where it is relevant, material from the work of others has been acknowledged.

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Chapter 1 – Introduction and Rationale

1.1 Ice sheets in the global climate system and the British-Irish Ice Sheet

Climate change, specifically global warming, is an issue at the forefront of scientific research which has prompted the need for a better understanding of ice sheets, both in a contemporary and palaeo-glaciological sense, largely due to the impact they have on global sea levels. Ice sheets are classified as being larger than 50,000 km^2 (Benn and Evans, 2010) and, currently, there are only two ice sheets on Earth: the Antarctic Ice Sheet (which is generally categorised into the East and West Antarctic Ice Sheets) and the Greenland Ice Sheet. The East Antarctic, West Antarctic and Greenland ice sheets have volumes of 21.7×10^6 km^3, 3×10^6 km^3 and 2.6×10^6 km^3, respectively, which equates to 57 m (Antarctica) and 6.5 m (Greenland) of sea level equivalent (Benn and Evans, 2010). An understanding of how past ice sheets responded to climate change is important help to predict how current ice sheets will respond to future climatic changes.

During the Last Glacial Maximum (LGM) ice sheets also existed in mid-latitude regions. The Laurentide Ice Sheet was the largest in the northern hemisphere and covered large parts of North America and is one of the most widely studied palaeo-ice sheets (Dyke and Prest, 1987; Stokes, 2017). It is clear from the glaciated terrain over many parts of Britain and Ireland that their landscapes were also once inundated by an ice sheet during the last glaciation; the British-

Irish Ice Sheet (BIIS), which was connected to the much larger Fennoscandian (or Eurasian) Ice Sheet (Andersen, 1981; Boulton *et al*., 1985, 1991; Sejrup *et al*., 2005; Clark *et al*., 2012). An important element of ice sheets, including the BIIS, are ice streams (Bennett, 2003). Ice streams are corridors of fast-flowing ice that move at a velocity greater than that of the ice sheet surrounding it and they are responsible for the majority of ice sheet discharge (Bindschadler *et al.,* 1998; Stokes and Clark, 1999, 2001; Bennett, 2003; Ó Cofaigh *et al.*, 2003, 2008; De Angelis and Kleman, 2005, 2007; Larter *et al.*, 2009). In recent years, ice streams have been shown to be instrumental in both the timing and dynamics of ice sheet deglaciation of the BIIS (Clark *et al*., 2012).

1.2 Contemporary and palaeo-ice streams

Ice streams are the most dynamic feature of an ice sheet with specific characteristics that include highly convergent flow patterns, sometimes including identifiable tributaries (Joughin *et al*., 1999); a trunk zone with rapid ice flow and sharply delineated shear margins (Raymond *et al*., 2001), and spatially focused sediment delivery at the grounding line (Alley *et al*., 1989) (Figures 1.1 and 1.2). Stokes and Clark (1999) stressed that ice streams are of major importance to ice sheet evolution because they are the main drainage route for large quantities of ice from ice sheets. For example, Bamber *et al.* (2000) suggested that up to 90% of the Antarctic Ice Sheet's drainage is through ice streams. Knowledge of the location of palaeo-ice streams is therefore of huge importance to ice sheet reconstruction due to the impact they have on ice sheet drainage networks and the location of ice domes and ice divides (Stokes and Clark, 2001). Furthermore, palaeo-reconstructions assist in understanding basal processes beneath ice streams, including the formation of subglacial bedforms (Stokes and Clark, 1999; 2001; Ó Cofaigh *et al.*, 2005; Hindmarsh and Stokes, 2008; Larter *et al.*, 2009; Stokes, in press). This is because it is difficult and expensive to examine the bed of contemporary ice stream settings, although this is a rapidly-evolving field (e.g. King *et al*., 2009).

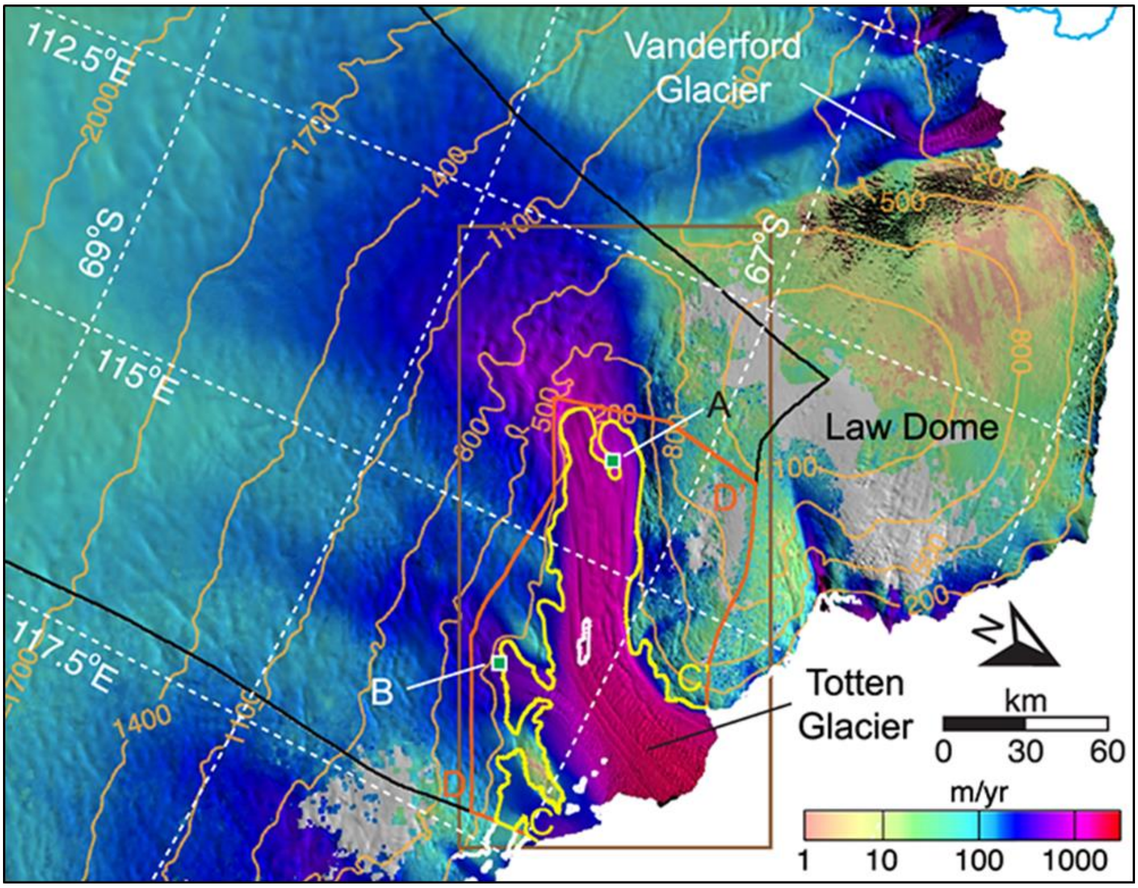

Figure 1.1 - Ice velocity of Totten Glacier, East Antarctica, colour coded on a logarithmic scale and overlaid on MODIS Mosaic of Antarctica image using ALOS PALSAR data from 2006 to 2010 and 2011 TDX/TSX, 2013 TDX/TSX, CSK, and Landsat-8 data. This shows the key features of an ice stream including its highly convergent flow patterns, trunk zone, sharply delineated margin, spatially focussed sediment delivery and distinct velocity field (Li *et al*., 2016).

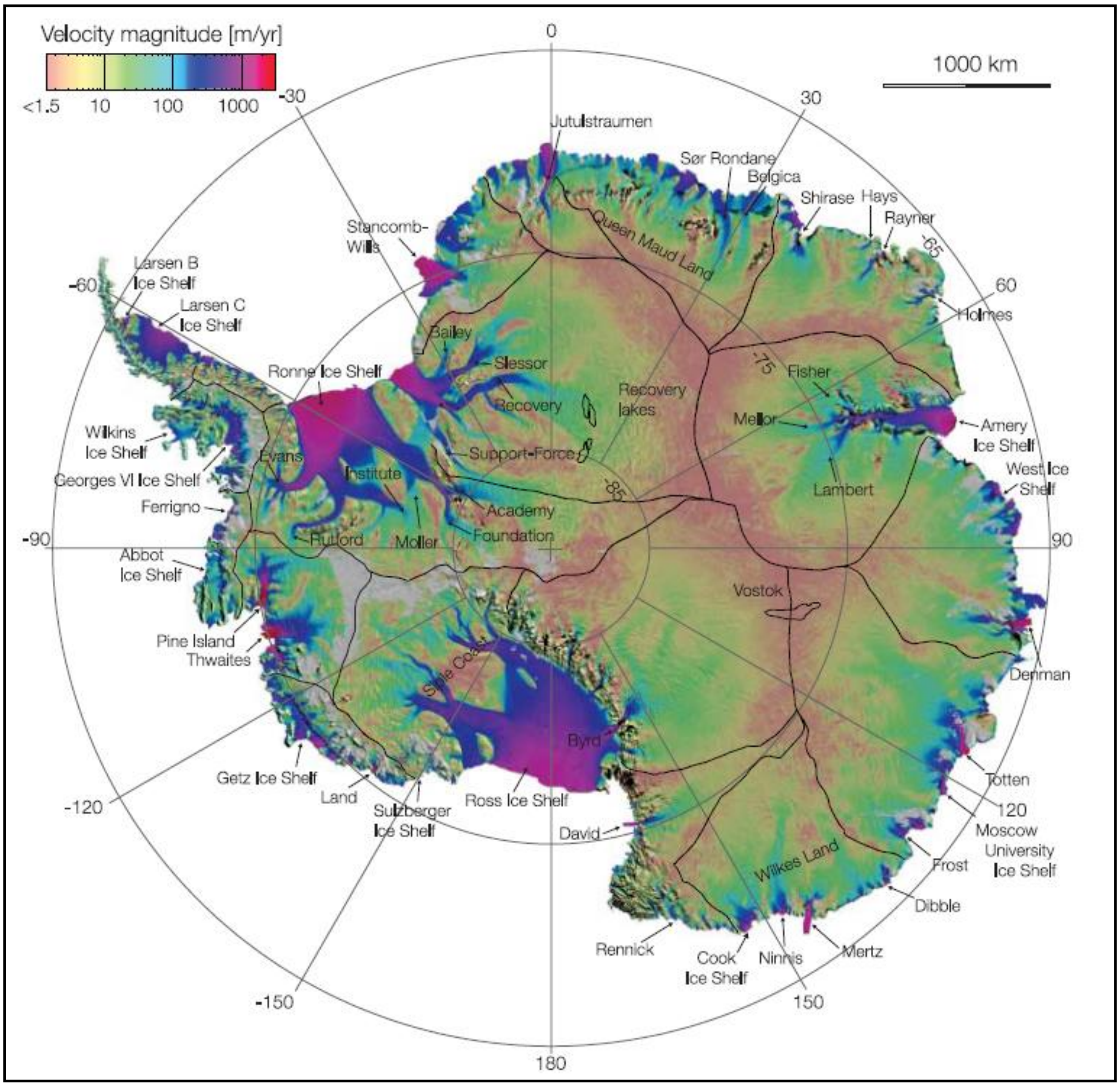

Fig1.2 - Antarctic ice velocity derived from ALOS PALSAR, Envisat ASAR, RADARSAT-2, and ERS-1/2 satellite radar interferometry, colour-coded on a logarithmic scale, and overlaid on a MODIS mosaic of Antarctica (Rignot *et al*., 2011).

There are two main types of ice streams: pure ice streams and isbraes/topographic ice streams (Margold *et al*., 2015). The former are not controlled by underlying topography whereas the latter are controlled by major topographic troughs. It is necessary to understand the differences between the two types of ice stream as this may affect the way they behave and respond to climate (Margold *et al*., 2015). Furthermore, ice streams are known to be hard-bedded or soft bedded ice streams and some may have a mixed bed. However, the identification of hard-bedded and mixed bedded ice streams is very much in its infancy compared to soft-bedded ice streams (Stokes, in press). Consideration of this concept of mixed-bed ice streams is essential for understanding the flow mechanisms of ice streams and improving ice sheet reconstructions (Krabbendam *et al*., 2016; Eyles *et al.*, 2016). Krabbendam *et al*. (2016) concluded that the consideration of both soft bed and hard bed landforms should result in more accurate reconstructions of past ice streaming activity. It is also the case that ice streams might transition from one type to another, e.g. a soft-bedded ice stream might gradually export its subglacial sediments such that patches of hard bed appear (e.g. Clark and Stokes, 2001).

Ice streams also have a connection with the climate system; they are thought to respond to climate (Jenkins *et al.*, 2010) and it has been discovered that ice streams have produced ice sheet instabilities large enough to drive climate change (Bond and Lotti, 1995). Therefore, accurate reconstructions of their behaviour under different climates help to predict how modern ice sheets will respond to future climatic changes (Stokes and Clark, 1999; Bamber *et al.*, 2000).

In view of the above, it is important to understand the history of the BIIS to allow us to fully understand how climate change influenced its retreat and the role of ice stream activity. The Firth of Forth area, South East Scotland, is a previously glaciated location and displays an abundance of glacial landforms. Numerical models (e.g. Boulton and Hagdorn, 2006; Hubbard *et al*., 2009) have highlighted this region as a possible location of a palaeo-ice stream, but very little work has been undertaken to test whether an ice stream operated in the region. Here lies the motivation for the present study.

1.3 The Forth

Numerous ice streams have been identified in the BIIS, namely the Irish Sea (Knight *et al.*, 1999; Roberts *et al*., 2007); Moray Firth (Merritt *et al.*, 1995); Strathmore (Merritt *et al.*, 2003); Tyne Gap (Beaumont, 1971; Livingstone *et al*.); Minch (Stoker and Bradwell, 2005); and Tweed ice streams (Everest *et al.*, 2005). The identification and consideration of these ice streams has resulted in improved and more accurate palaeo-glaciological reconstructions of the BIIS. Clark *et al*. (2012) suggested that the BIIS is a useful analogue for the West Antarctic Ice Sheet due to a large proportion of it being marine-based and drained by ice streams. Ice stream identification has further advanced BIIS reconstructions especially considering that it deglaciated in response to rising temperatures and sea levels (Hubbard *et al*., 2009; Scourse *et al*., 2009; Clark *et al*., 2012; Finlayson *et al*., 2014). Clark *et al*. (2012) noted that ice stream areas retreated at a faster rate than inter-stream areas. Clark *et al.* (2003) and Clark *et al.* (2004) also suggested that palaeo-glacial reconstructions of the BIIS have been improved by accurately evaluating glacial geomorphology through the consideration of ice stream activity. A further reason for undertaking the present study is that BIIS ice streams are understudied compared to other ice sheets such as the Laurentide (Andrews *et al.*, 1985; Dyke and Morris, 1988; Hicock, 1988; Boyce and Eyles, 1991; Laymon, 1992; Kaufman *et al.*, 1993; De Angelis and Kleman, 2008; Cofaigh *et al.*, 2010; Margold *et al.*, 2015), Antarctic (Livingstone *et al*., 2012) and Fennoscandian Ice Sheet (Ottesen *et al*., 2005, 2008). Furthermore, and as noted above, the Forth area has not been formally identified as an ice stream, possibly because it is has a mixed bed featuring landforms found on both soft and hard beds, such lineations influenced by bedrock roughness (e.g. crag-and-tails). However, numerical models (Fig 1.3) generate an ice stream at this location that is large (exact size not specified) and appears to have influenced the other ice streams on the east coast due to its size and catchment area. Identification and analysis of the glacial geomorphology of the Forth area makes it possible to identify the glacial and subglacial conditions of the last glaciation (Late Devensian). This research aims to understand if there was an ice stream at this location and, if so, what kind of subglacial signal did it leave and what influenced its behaviour?

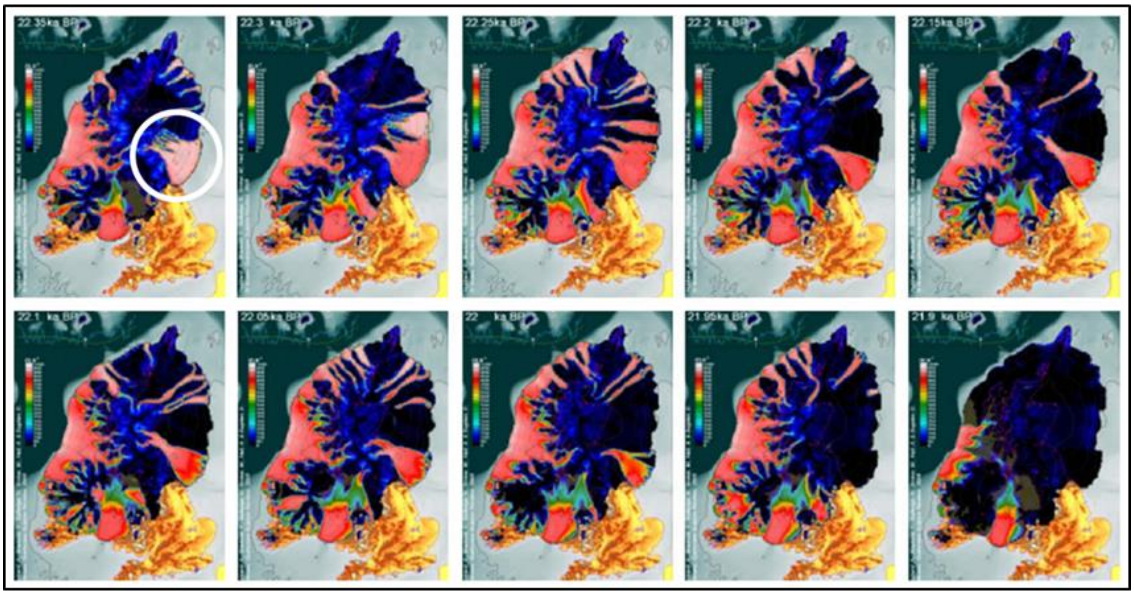

Fig 1.3 - A numerical model output showing ice stream activity across the Britain (Hubbard *et al*., 2009). The red areas indicate ice streaming. The Forth area is highlighted in the white circle in the first image.

1.4 Aims and Objectives

The overall aim of this project is to determine if the Firth of Forth area exhibits glacial geomorphological evidence of palaeo-ice stream activity:

The specific objectives are to:

- Examine and characterise the glacial geomorphology of the Forth region using remote sensing
- To use established criteria, from both soft-bedded and hard-bedded ice streams (e.g. Stokes and Clark, 1999; Krabbendam *et al.,* 2016), to test whether the Firth of Forth was the location of an ice stream
- To examine the subglacial landsystem and determine the relative roles of bedrock geology and topography
- To reconstruct the general chronology and glacial history of the area
- To understand ice stream influence on regional ice sheet history

Chapter 2 – A Review of the literature on ice stream landsystems.

2.1. Introduction

Ice stream beds can be broadly classified as either soft, hard or mixed (see Section 1.2). Soft-bedded ice streams generally refer to situations where the ice stream was underlain by a metres-thick layer of deformable till (e.g. Alley *et al*., 1986; Stokes and Clark, 1999; Clark and Stokes, 2005; Livingstone *et al*., 2012). Hard-bedded ice streams are much rarer, but generally refer to those situations where ice streaming occurred over much harder crystalline bedrock and with only minimal sediment cover (Roberts and Long, 2005; Bradwell *et al*., 2008; Eyles, 2012, Eyles and Putkinen, 2014; Krabbendam *et al*., 2016). Mixed bed ice streams are those whose bed shares characteristics of both of the previous types, but have been very rarely reported. Palaeo-ice streams with soft beds have been more extensively studied and criteria to identify them were developed in the late 1990s (Stokes and Clark, 1999). They are easier to identify and study because the sediments are easily deposited, remoulded and eroded and, as a result, tend to leave a very clear glacial geomorphological signature. Ice streams can, however, operate over hard beds (Roberts and Long, 2005; Krabbendam *et al*., 2016). Hard beds are much more resistant to erosion which results in reduced sediment availability and less obvious landforms, as well as more difficulty in identifying, for example, the lateral shear margins. Hard-bedded ice streams had not been studied in detail until relatively recently (see review in Krabbendam *et al*., 2016), although the onset zones of numerous palaeo-ice streams have been recognised to have hard beds (see review by Livingstone *et al*., 2012).

This chapter will review the literature on ice stream landsystems. First, it will look at soft-bedded ice stream landsystems (Section 2.2) and their associated landforms; drumlins (Section 2.2.1), mega-scale glacial lineations (MSGLs; Section 2.2.2), ice stream shear margin moraines (Section 2.2.3) and ribbed moraines (Section 2.2.4). It will go on to review the literature on hard-bedded ice stream landsystems (Section 2.3) and their associated landforms; roches moutonnées and whalebacks (Section 2.3.1), bedrock mega-grooves (Section 2.3.2), crag-and-tails (Section 2.3.3) and rock drumlins (Section 2.3.4). Finally, the concept of mixed-bed ice streams will be explored (Section 2.4).

2.2. Soft-bedded ice stream landsystems

Menzies (1979) stated that "the first step in understanding the landform must be the understanding of the system" (p. 349). Individual landforms are not unique features of glacial landscapes but rather one product of the system. A landsystem is an area of specific landform assemblages or terrain attributes that are different to the characteristics of surrounding areas (Evans, 2005; Benn and Evans, 2010). Furthermore, it is an area in which past climatic conditions, erosional and depositional processes and underlying geology are expressed in the patterns of surface landforms.

The concept of landsystems became popular in the 1940s as a result of the Commonwealth Scientific and Industrial Research Organization reports (Evans, 2005) and has since undergone expansion and refinement. Fookes *et al.* (1978) was the first to introduce glacial landsystems in order to provide process-form classifications of glacigenic landform-sediment assemblages to engineers and his ideas were later developed by Eyles (1983). Since then, there have been many advances in the landsystem concept, of which a wide variety now exist (Evans, 2005) including the palaeo-ice stream landsystem (e.g. Clark and Stokes, 2005).

Ice stream landsystems can be either marine or terrestrial depending on the location of their terminus. Terrestrial ice streams terminate in a proglacial lake or splayed lobe (Clark and Stokes, 2005) (Fig. 2.1). It is important to note that the geomorphology left behind may represent a complex amalgamation of ice stream activity because ice streams typically operate from hundreds to thousands of years (Stokes *et al*., 2016). Clark and Stokes (2005) hypothesised that the resultant landsystems will take one of two forms; ‘rubber-stamped’ landsystem or ‘smudged’ landsystem. The rubber-stamped or ‘isochronous’ landsystem occurs when the ice stream stops and preserves the subglacial geomorphology during deglaciation. Smudged or ‘time transgressive’ landsystems occur when ice streams function throughout numerous cycles of advance and retreat or just retreat and become modified (Fig. 2.2).

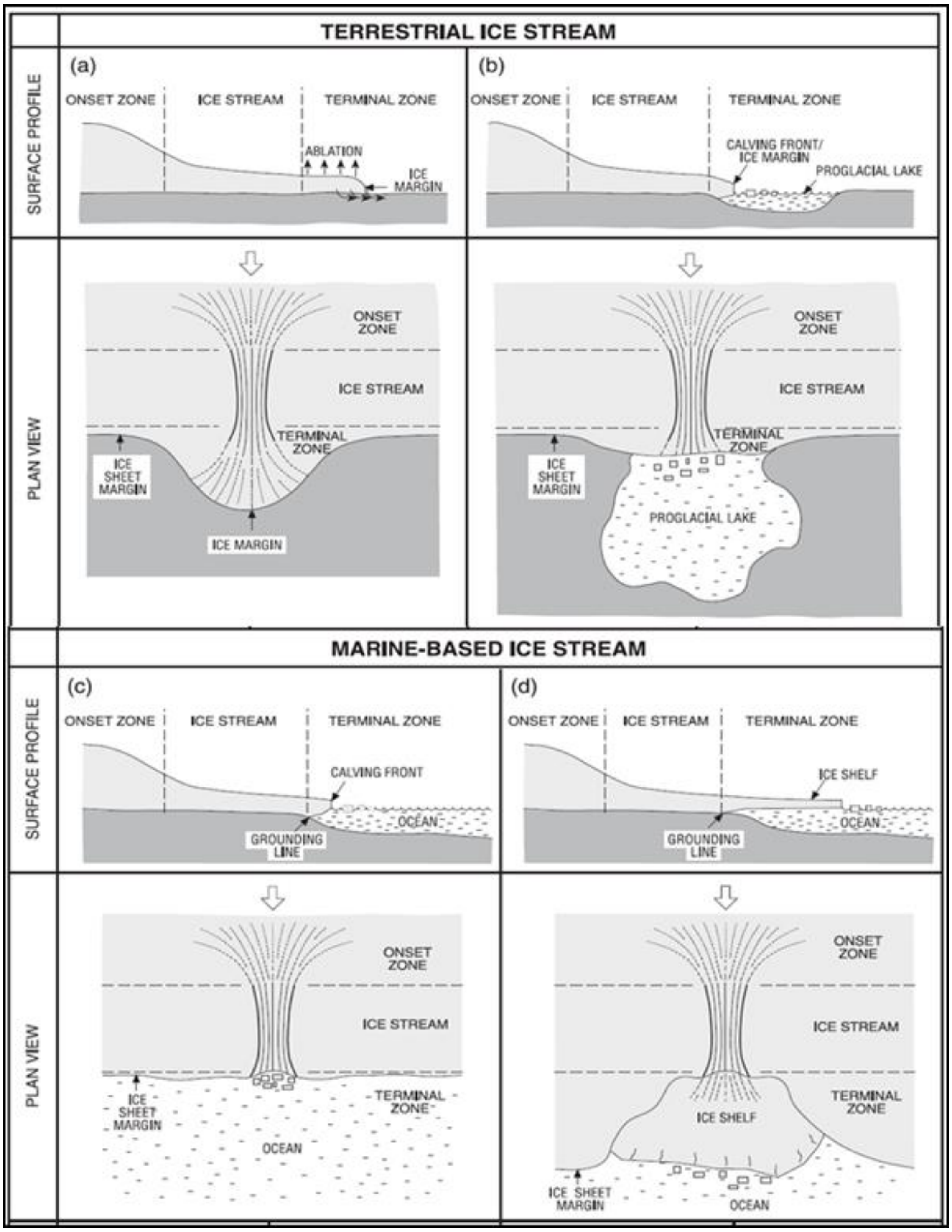

Figure 2.1 - Simplified configurations of terrestrial and marine based ice streams. (a) terrestrial ice stream terminating as a large splayed lobe. (b) terrestrial ice stream terminating into a proglacial lake. (c) marine ice stream terminating into open water as ice bergs. (d) marine ice stream terminating into a floating shelf (Clark and Stokes, 2005).

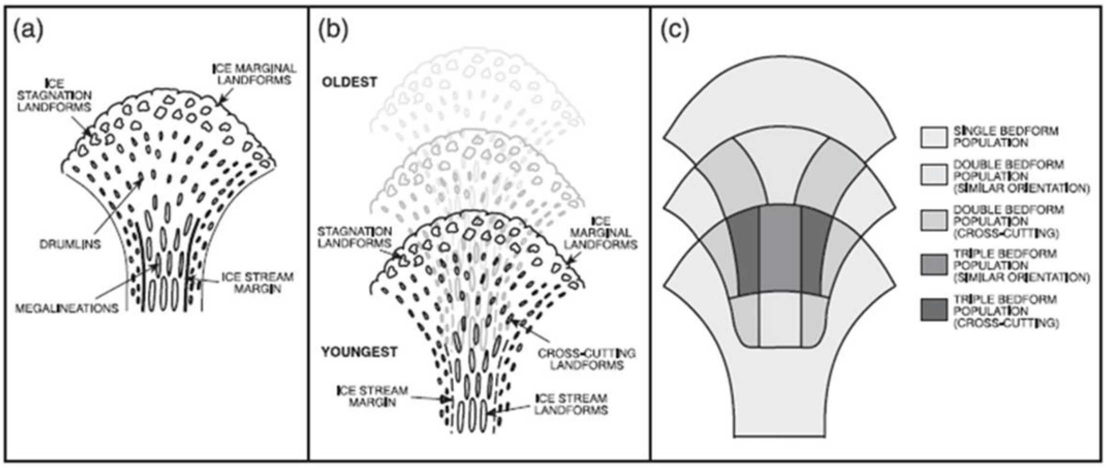

Figure 2.2 - (a) the 'rubber-stamped' landsystem representing an ice stream that switched off and retreated without modifying the landscape. (b) the 'smudged' landsystem representing an ice stream that continued operation through deglaciation and caused overprinting. (c) schematic diagram of the landform assemblages expected with a 'smudged' landsystem (Clark and Stokes, 2005).

Stokes and Clark (1999) and Clark and Stokes (2005) formulated a set of distinctive geomorphological criteria for identifying palaeo-ice streams on soft beds based on the characteristics of contemporary ice streams, conventional glacial geomorphology theories, and investigations of palaeo-ice streams with soft beds (Table 2.1). The component features of these landsystems will now be reviewed.

Table 2.1 - Geomorphological criteria for identifying palaeo ice-streams (Clark and Stokes, 2005).

Contemporary ice stream characteristics	Proposed geomorphological signature
Characteristic shape and dimensions	Length > 150 km Width > 20 km
	Highly convergent flow patterns (clear onset zone)
Sharply delineated margin	Abrupt lateral margins
	Shear margin moraines
Rapid velocity	Highly attenuated bedforms (elongation ratio >10:1)
	Boothia-type erratic dispersal trains
Distinct velocity pattern	Expected spatial variation in bedform elongation ratios
Focused sediment delivery	Submarine till delta or trough-mouth fan

2.2.1. Drumlins

Drumlins are a glacial lineation defined as "round, oval or elongated hills" (Embleton and King, 1975). They have a long axis which is orientated parallel to the direction of ice flow (Benn and Evans, 2010). Drumlins can be used to reconstruct the direction of ice flow in an area (Benn and Evans, 2010). Clark *et al*. (2009) found that the lengths, widths and elongation ratios of drumlins form unimodal distributions and that average drumlin lengths are 629 m, average widths are 209 m and average elongation ratio is 2.9 m. Drumlins have been found and used to identify palaeo-ice streams in a huge number of locations including the British-Irish ice sheet (Clark *et al.*, 2012) and Patagonia (Lovell *et al.*, 2011). They have also been found under modern ice streams in Antarctica (Campo *et al.*, 2017; Menzies *et al.*, 2016) and Iceland (Lamsters *et al.*, 2016). Although drumlins can clearly form under slow-moving parts of an ice sheet, they are typically associated with increasing ice velocities and elongation ratios in the onset zone of palaeo-ice streams (e.g. Stokes and Clark, 2003; Angelis and Kleman, 2008). O'Cofaigh *et al*. (2002) looked at the evolution of subglacial bedforms along a palaeo-ice stream on the Antarctic Peninsula continental shelf. They concluded that bedforms get progressively more elongate with distance along the trough which indicates increasing flow velocities.

2.2.2. Mega-scale glacial lineations

Mega-scale glacial lineations (MSGLs) were first identified by Clark (1993) as large-scale, streamlined lineations of drift of much greater proportions than drumlins and mega-flutes. They have average lengths ranging from 1000 m to 2000 m and spacings of around 200 m to 300 m (Spagnolo *et al*., 2014). Clark (1993) suggested that such large scale landforms can only form under specific subglacial conditions including extremely rapid ice flow. MSGLs have been found on numerous palaeo-ice stream beds such as Antarctica (Spagnolo *et al*., 2017; Evans *et al*., 2016; Spagnolo *et al*., 2016) and the Laurentide (O'Cofaigh *et al*., 2013). Livingstone *et al*. (2012) reviewed Antarctic palaeo-ice streams. They identified the presence of MSGLs, drumlins, grooved bedrock and meltwater channels. The presence of MSGLs under contemporary ice streams was first confirmed by King *et al.* (2009) from a radar survey of the Rutford ice stream in West Antarctica (Fig. 2.3a). The landforms are identical in morphology as those identified on palaeo-ice stream tracks (Fig. 2.3b). King *et al.* (2009) found that the Rutford MSGLs were composed of soft ‘dilatant’ till underlain by stiff tills, which appears to be similar to the situation reported for numerous MSGLs on the bed of palaeo-ice streams around Antarctica (Cofaigh *et al.*, 2002; Dowdeswell *et al.*, 2008; Larter *et al.*, 2009). The confirmation of the existence of MSGLs beneath the Rutford Ice Stream considerably strengthens the relationship between these bedforms and fast flowing ice. Stokes *et al.* (2013) analysed around 46,000 landforms on the bed of the Dubawnt Lake palaeo ice stream. They found lineations that exceeded 10 km in length and found that 23% of these lineations had elongation ratios of >10:1. The highly elongate features identified were interspersed with shorter drumlin features. The longer bedforms analysed were, in general, narrower which suggests the length of these bedforms developed more quickly than their width. They concluded that MSGLs obtain their length very quickly under conditions of rapid ice flow.

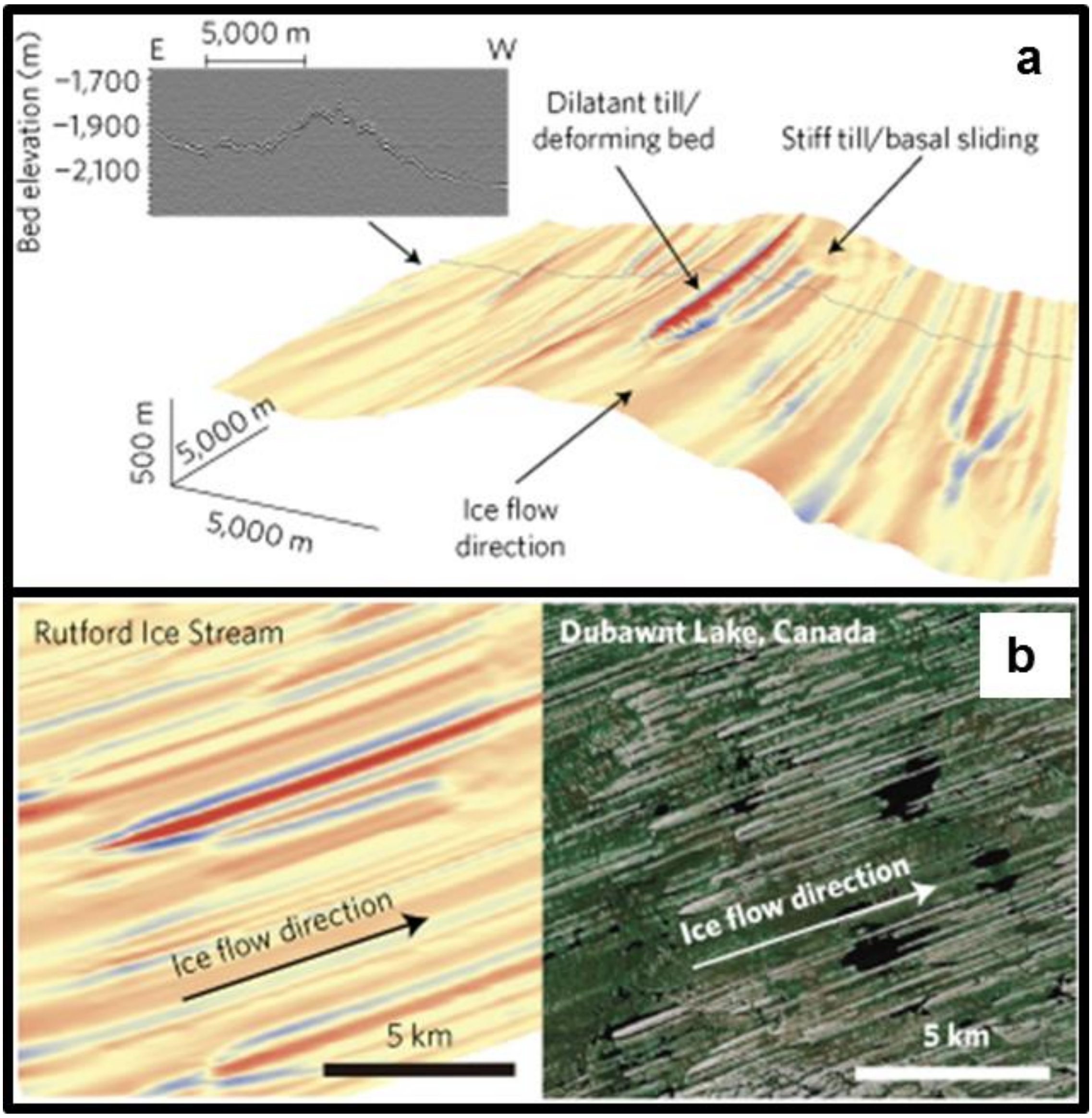

Figure 2.3 - (a) Three-dimensional image of the bed of Rutford Ice Stream viewed from the northeast showing highly elongate MSGLs. (b) Rutford bedforms compared with landsat satellite image of relict bedforms from the Dubawnt Lake palaeo-ice stream bed northern Canada (King *et al*., 2009).

2.2.3 Ice stream shear margin moraines

Ice stream shear margin moraines are large subglacial ridges found at the margins of an ice stream (Dyke and Morris, 1988; Stokes and Clark, 2002). They can be up to several kilometres in length and up to tens of metres high and wide. They are thought to indicate the shear zone at ice stream margins and separate fast and slow ice flow (Dyke and Morris, 1988). There are limited observations of them on ice stream beds and, as a result, details of their formation is unknown (Hindmarsh and Stokes, 2008). However, Stokes and Clark (2002) speculated about a number of possible formation mechanisms, such as meltwater processes, lateral advection of sediment towards the shear margin, deposition of entrained debris along the margin, and differential erosion and downstream sediment recycling. Ice stream shear margin moraines have been used in the identification of various palaeo-ice stream such as the M'Clintock Channel Ice Stream, Canada (Clark and Stokes, 2001), the Strathmore Ice Stream, Scotland (Golledge and Stoker, 2006); and the Vestfjorden-Trænadjupet, Norwegian Channel and Bear Island Trough palaeo-ice streams (Ottesen *et al.*, 2005).

2.2.4. Ribbed moraines

Ribbed moraines were first described by Lundqvist (1989) as a series of parallel moraine ridges lying perpendicular to ice flow. Their height is generally around 10 - 20 m and widths are usually 50 – 100 m (Lundqvist, 1989). Although ribbed moraines are generally thought to form under slow-moving ice and are primarily located close to ice divides (Kleman and Hättestrand, 1999), there are a handful of reports of them on ice stream beds, superimposed on drumlins and mega-scale glacial lineations in locations such as the Dubawnt lake palaeo-ice stream, Canada (Stokes and Clark, 2003; Stokes *et al*., 2006; Stokes *et al*., 2008). In these cases, they are inferred to represent sticky spots that developed as the ice stream shut-down (e.g. Stokes *et al*., 2008). Ribbed moraines have also been identified in some ice stream onset zones, where they are thought to results from stick-slip behaviour between cold and warm-based ice (Dyke and Morris, 1988; Dyke *et al*., 1992; De Angelis and Kleman, 2008).

2.2.5. Summary

As stated above, a vast number of soft-bedded ice streams have been identified, using the geomorphological criteria detailed above. Livingstone *et al.* (2012) analysed Antarctic palaeo-ice streams (Fig 2.4) and concluded that the landforms displayed spatial variability dependent upon the influence of substrate, subglacial processes and flow velocity. Margold *et al*. (2015) reviewed ice streams in the Laurentide Ice Sheet (Fig 2.5). They conclude that most of the larger ice streams were controlled by topography although some were more spatially dynamic and existed in sinuous tracks. They note that underlying geology is important in controlling the pattern and density of ice streams.

To summarise, a soft-bed system is characterised by distinct geomorphological criteria; highly convergent flow patterns, abrupt lateral margins, shear margin moraines, highly attenuated bedforms such as drumlins and MSGLs, distinct velocity pattern and a focussed sediment delivery (Stokes and Clark, 1999; Clark and Stokes, 2005).

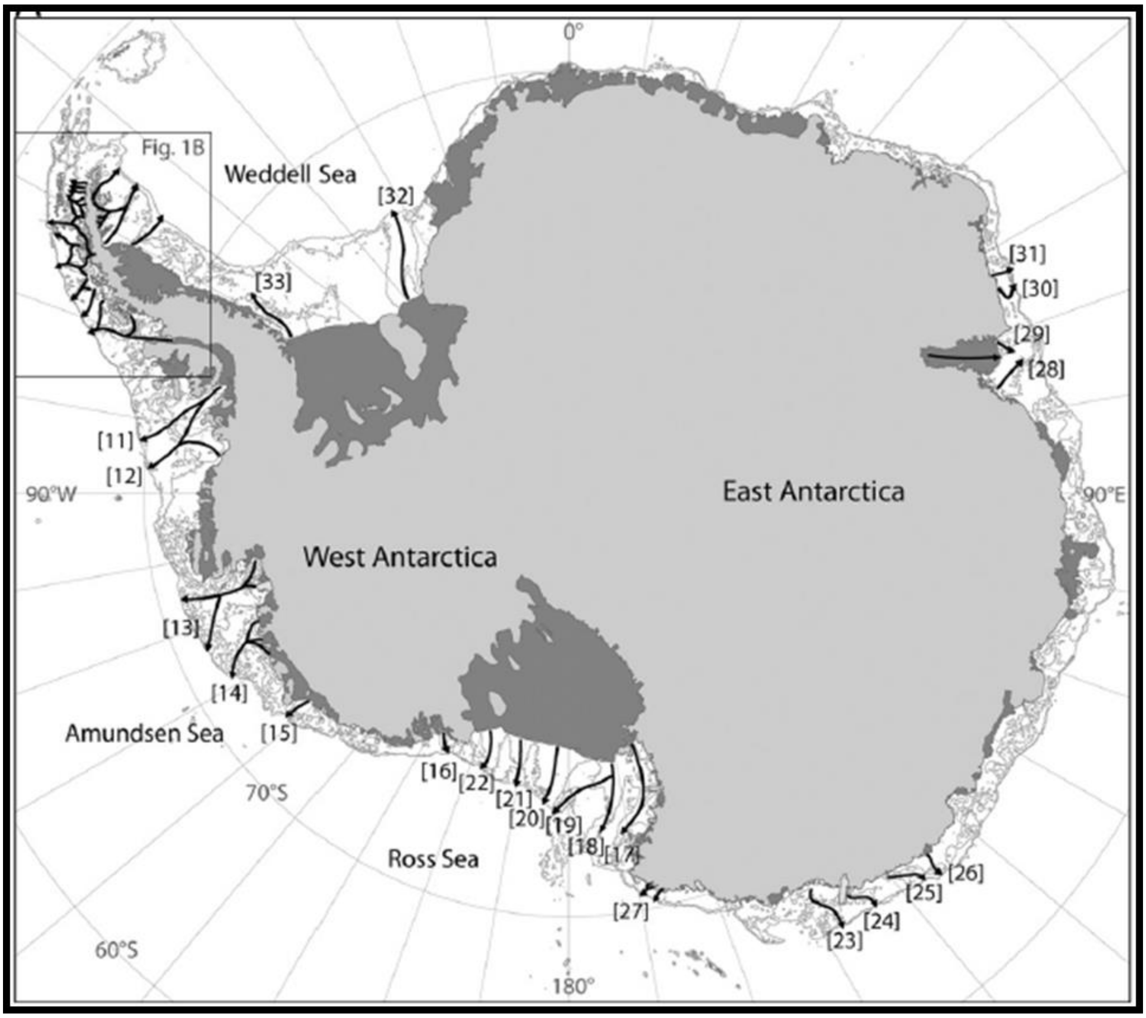

Figure 2.4 - Locations of the main palaeo-ice streams known on the Antarctic continental shelf. Approximate locations of ice streams are depicted by a black arrow and the numbers refer to corresponding citation and evidence outlined in Livingstone *et al*., 2012.

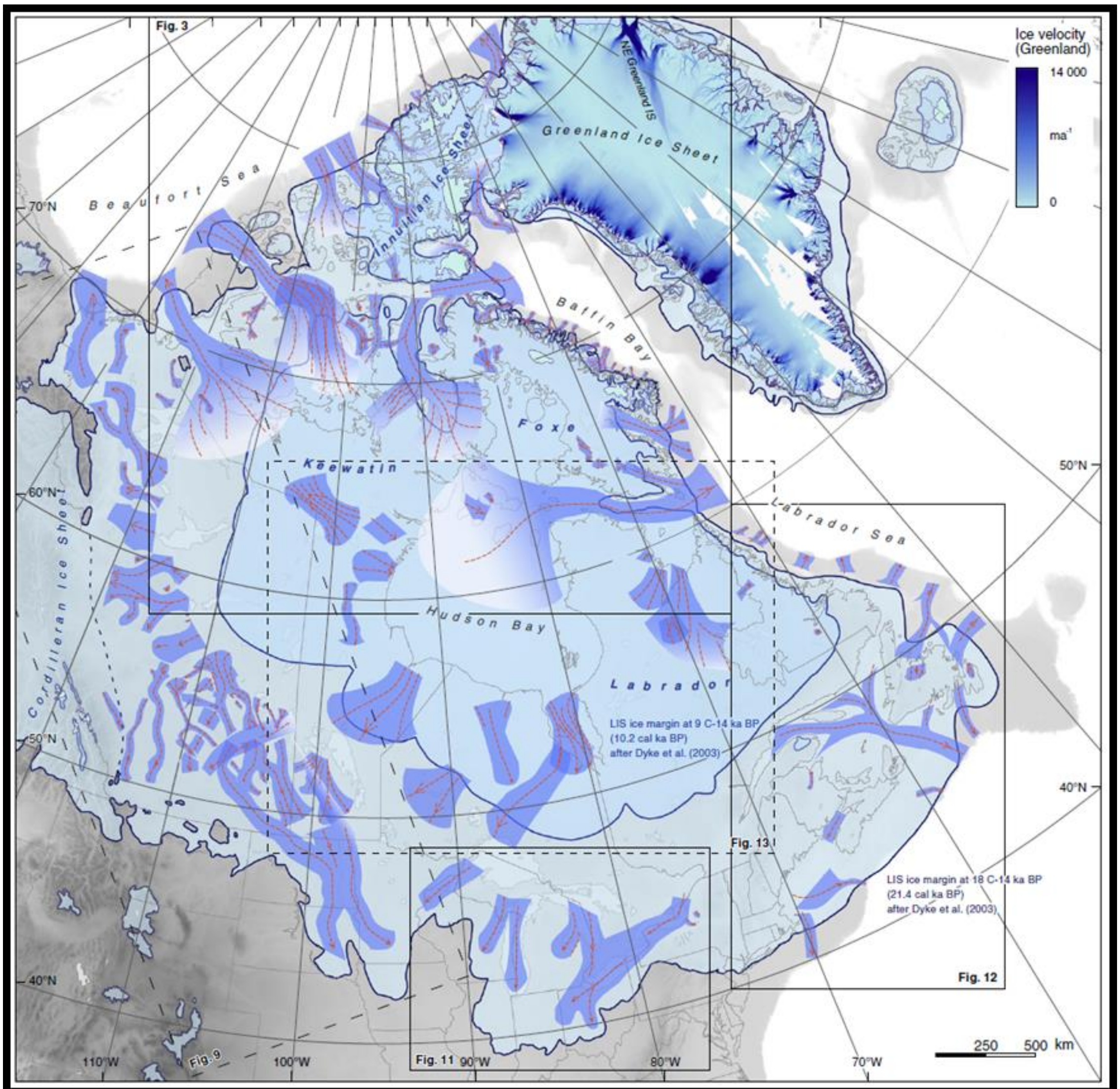

Figure 2.5 - Ice streams of the Laurentide ice sheet. For further detail see Margold *et al.* (2015).

2.3. Hard-bedded ice stream landsystems

Unlike soft bedded ice streams, there has been much less research identifying ice streams occurring over hard beds and it is only in recent years they have become a focus of research (Roberts and Long 2005; Shaw *et al*., 2006; Bradwell *et al*., 2008; Ottesen *et al*., 2008; Jezek *et al*., 2011; Eyles, 2012; Eyles and Putkinen, 2014; Bradwell and Stoker, 2015; Krabbendam *et al*., 2016).

There are a number of landforms that have been identified on hard-bedded ice streams such as meltwater channels, rock drumlins, roches moutonnées, whalebacks, bedrock megaridges, megagrooves and crag-and-tails (See Krabbendam *et al*., 2016 for review). Different types of streamlined bedrock such as elongate megagrooves, megaridges and rock drumlins have all been identified on palaeo- and contemporary ice stream beds (e.g. Bradwell, 2005; Jezek *et al*., 2011; Eyles, 2012, Eyles and Putkinen, 2014) in areas such as the British Isles (Bradwell and Stoker, 2015), Norway (Ottesen *et al*., 2008), Antarctica (Graham *et al*., 2009) and Canada (Shaw *et al*., 2006), suggesting that a distinctive set of landforms develop in areas of hard bed (e.g. crystalline bedrock). However, many studies point to hard bed streamlining settings being followed by mixed-bed and soft-bed streamlining down ice as either eroded sediment is transported down the ice stream or as ice encounters geologically softer terrain (Lowe and Anderson, 2002; Bradwell and Stoker, 2015).

Roberts and Long (2005) investigated Jakobshavns Isbrae, W. Greenland, which has a hard bed; and highlighted important differences between the landsystems produced on ice streams with hard beds and soft beds. Soft-bedded ice streams produce bedforms with high elongation ratios (Stokes and Clark, 1999) (Table 2.1), that are often the product of a single flow phase. In contrast, bedrock bedforms are the potential product of multiple glacial cycles, and hence several cycles of erosion. As such, the mechanisms that control their evolution, particularly elongation ratios, are very different to soft bedded ice stream systems. Prolonged and repeated erosion along fixed basal ice flow pathways may produce highly elongate bedforms at a macro- or megascale, but repeated, small-scale, process such as abrasion and plucking may reduce bedform length at the meso and micoscale (Roberts and Long, 2005). Hence, as a result of these complex feedbacks, the relationships between bedrock bedform evolution and fast ice flow remain poorly understood.

2.3.1. Roches moutonnées and whalebacks

Roches moutonnées are asymmetric erosional bedrock forms with abraded stoss slopes and plucked lee slopes. They range in length from less than one meter to several hundreds of meters (Sugden *et al*., 1992; Benn and Evans, 2010). Their orientation is controlled by ice flow direction; the stoss face is found up-ice and the lee face, down ice. This morphology reflects differing basal stresses exerted on the bedrock and bedrock hardness/structure (Fig. 2.6). High ice overburden pressures on the stoss side lead to abrasion, polishing and striation. On the lee side, cavity formation and pressure reduction lead to freeze/thaw fracture promotion and plucking.

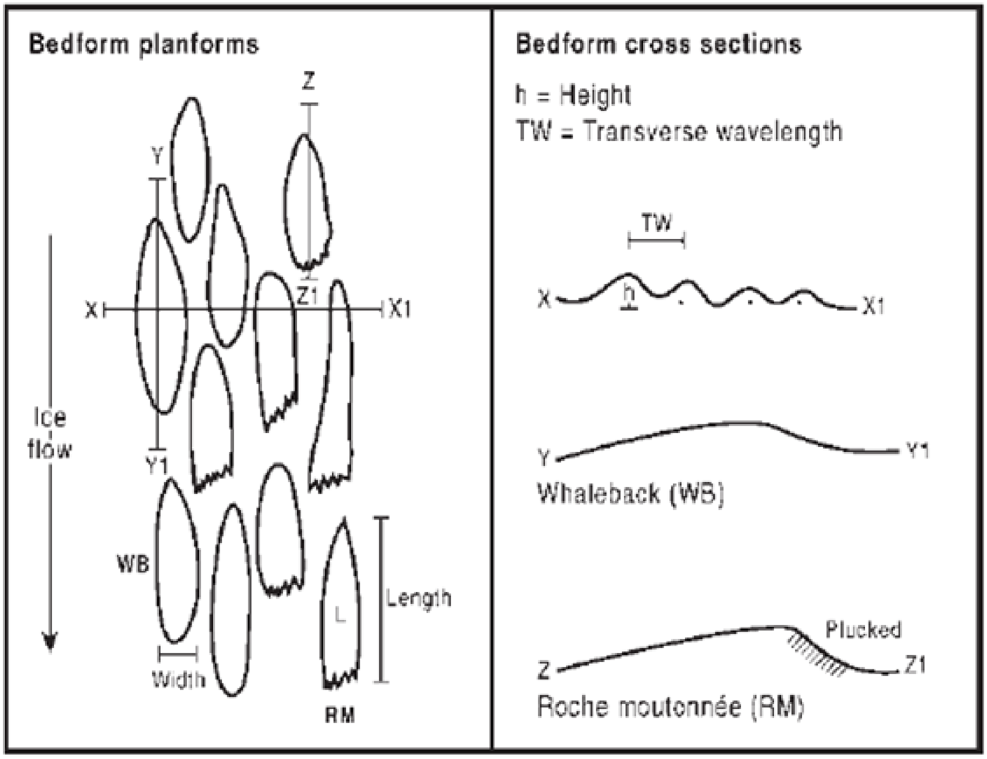

Figure 2.6 - Roche moutonnée and whaleback planforms and cross sections (Roberts and Long, 2005).

Whalebacks are symmetrical streamlined bedrock forms with striae and p-forms covering them (Fig. 2.6). They do not exhibit the plucked lee faces common on roches moutonnées which suggest that low pressure cavities do not form on their lee-sides (Benn and Evans, 2010). Roberts and Long (2005) suggested that, in the case of the Jakobshavns Isbrae, whaleback bedforms were common with an especially high density beneath the ice stream. In contrast, roches moutonnées were more common beneath the slow-flowing ice sheet and displayed lower densities. Roberts and Long (2005) linked this is to a complex set of feedbacks whereby thicker ice beneath ice streams areas led to increased ice strain heating, increased basal melt and higher ice viscosities; a combination of factors that effectively suppressed cavity development leading to the preferential development of whale backs over roches moutonnées in hard-bedded stream areas. Evans (1996) also identified whalebacks with topographically controlled ice streams in British Columbia, Canada, where they were also thought to reflect thick, rapidly-moving warm-based ice.

2.3.2. Bedrock megagrooves

Bedrock megagrooves are linear features, tens of meters wide and deep, eroded in bedrock. They were first described by Smith (1948) and Zumberge (1954) in the Northwest Territories of Canada and Isle Royale in Lake Superior, USA. Bradwell (2005) and Bradwell *et al.* (2008) suggested that they can be used to determine erosive power and therefore flow velocity of ice sheets and they associated them with the onset zone of the Minch palaeo-ice stream in North West Scotland (Bradwell *et al.*, 2008). Bedrock megagrooves have since been shown to be common in hard bed settings (Jezek *et al*., 2011; Roberts *et* *al*., 2010; Eyles and Putkinen, 2014) but their exact mode formation and relationship to fast ice flow still remains poorly explained. Eyles and Putkinen (2014) specifically identify the onset zone of the Laurentian Channel ice stream characterised by glacially-megalineated bedrock terrain carved by fast flowing ice.

2.3.3. Crag-and-tails

Crag-and-tail landforms are classic and iconic features formed by glaciers and ice sheets. During glacial activity, ice flow removed the softer rock, leaving the harder plugs behind. The harder rock acts and a barrier; hence the tail form. The existence of these landforms in the area implies ice flow and records its direction. The length of these forms can also indicate ice velocity. Castle Rock in Edinburgh is an example of such a landform. The crag portion is basalt which is firm and resilient and the tail is composed of sedimentary strata which is less resistant (Benn and Evans, 2010) (Fig. 2.7). They have been identified in numerous ice stream locations such as the Irish Ice Sheet (Greenwood *et al.*, 2008), the Norwegian Channel Ice Stream (Ottesen *et al.*, 2016) and Rijpfjorden and Duvefjorden, northern Nordaustlandet, Svalbard (Fransner *et al.*, 2017).

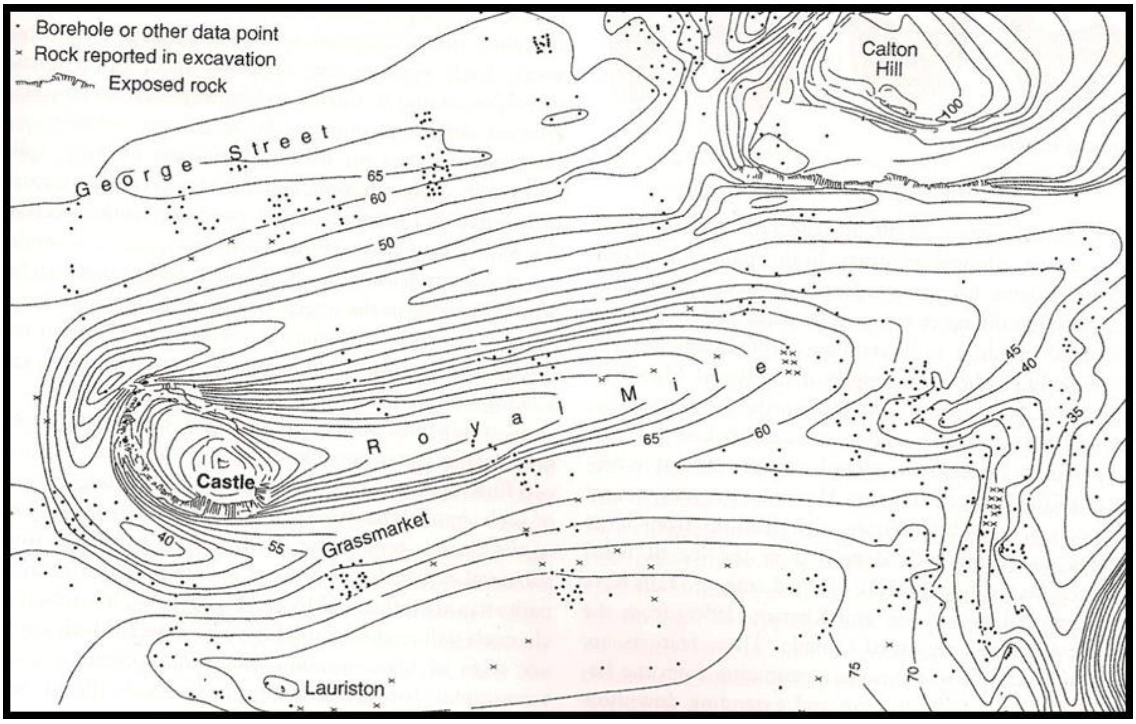

Figure 2.7 - Castle Rock, Edinburgh. This is a classic Crag-and-Tail landform in the Firth of Forth region (Benn and Evans, 2010).

2.3.4. Rock drumlins

Rock drumlins are bullet-shaped bedrock landforms (Eyles, 2012). They have been known as ‘tadpole rocks’ (Dionne, 1987) and are asymmetrical with steep stoss faces and gently tapering lee sides (Benn and Evans, 2010). The first rock drumlins to be identified were in central New York state by Fairchild (1907). They have also been identified in locations such as Scotland and Greenland (Gordon, 1981), Northern Ireland (Knight, 1997), Chile (Glasser and Harrison, 2005) and Canada (Eyles, 2012). Eyles (2012) analysed bedrock forms created by the Saginaw-Huron Ice Stream, Canada, and stated that rock drumlins are the most common bedrock landforms found on the Bruce Peninsula, the Manitoulin Island and the Niagara Escarpment. Eyles (2012) also found that the orientation of the rock drumlins he identified were, in the most part, independent of bedrock structures. The onset zone of this palaeo-ice stream is characterised by hard bed landforms.

2.3.5 Summary

As stated above, numerous hard bedded ice streams have been identified, both palaeo and modern. Krabbendam *et al*. (2016) described and analysed a number of hard-bedded ice streams (Fig 2.8) and concluded that their beds are dominated by an assortment of large scale, elongate bedrock forms. They found that the signatures were visible on both crystalline shield rock surfaces and on weaker sedimentary rocks. They highlight that the consideration of hard-bedded landforms in palaeo-reconstructions will lead to the identification of more ice streams as well as tracing existing imprints further up ice into onset zones that are dominated by bedrock.

To summarise, a hard bed system is characterised by large fields of kilometre-scale glacial lineations containing rock drumlins, megagrooves and megaridges at the large scale (Krabbendam, 2016) and whalebacks and rouches moutonnees at the small scale (Roberts and Long, 2005). The character and occurrence of these forms is heavily influenced by bedrock properties like hardness and fracture spacing. Finally, they are erosional bedforms, formed by focused abrasion or lateral plucking, depending on bedrock type.

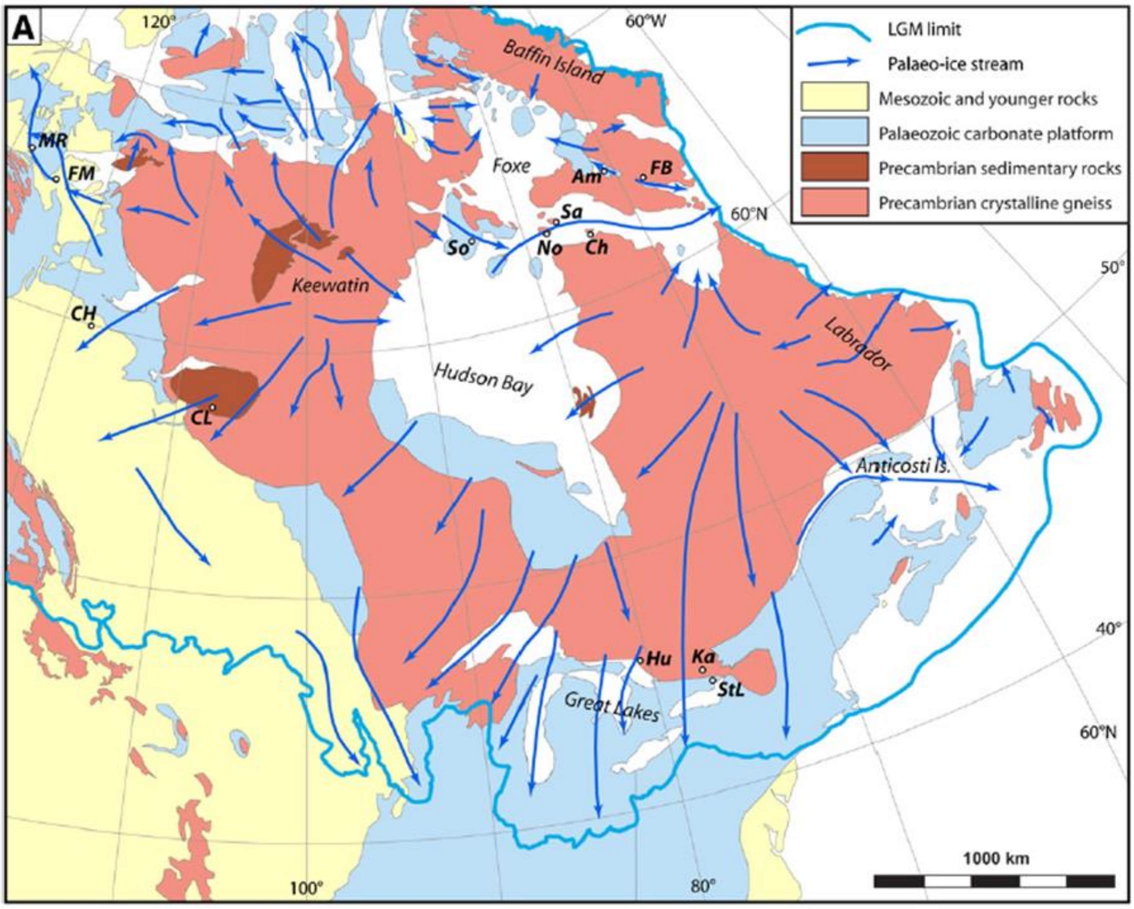

Figure 2.8 - Laurentide Ice Sheet with reported palaeo-ice streams, simplified bedrock geology, extent at Last Glacial Maximum (Krabbendam *et al.*, 2016).

2.4. Mixed-bedded ice stream landsystems

Palaeo-ice streams occurring over a mixed bed (bedrock and sediment) have received much less attention than hard and soft bedded, but hard to soft transitions (i.e. mixed bed settings) are being increasingly recognised (Lowe and Anderson, 2002; O Cofaigh *et al.,* 2013, Roberts *et al.,* 2013; Bradwell and Stoker; 2015; Dove *et al*., 2015). Onset zones are often dominated by bedrock landforms such as meltwater channels; rock drumlins that are transitional to streamlined megaridges/megagrooves and crag and tails as ice flow converges and trunk zones develop. Such bedforms are then transitional to soft bedded landforms down flow as sediment thickens and ice velocity increases (e.g. elongated drumlins; MSGLs). For example, the West Antarctic shelf is characterised by a clear bedrock-sediment boundary which displays a distinctive bedform imprint (Fig. 2.9; Graham *et al*., 2009). Both Lowe and Anderson (2002) and Graham *et al*. (2009) report meltwater channels and cavities upstream in bedrock areas that gave way to streamlined bedrock bumps, drumlins and grooves as flow converges. As ice then moves across the transition from hard to soft bedded conditions, streamlined bedforms (MSGLs and drumlins) and grounding zone wedges evolve as the ice advects and moulds sediment offshore (Figs. 2.9; 2.10). Ottesen *et al.* (2008) also investigated a palaeo-ice stream track on the northern Norway shelf and found that it crossed bedrock-sediment boundary much like that observed in West Antarctica, and more recent papers support this model with streamlined, bedrock bedform assemblages now reported in up-ice, onset zone settings formed beneath the last British Irish Ice Sheet (Bradwell and Stoker, 2015; Dove *et al*., 2015).

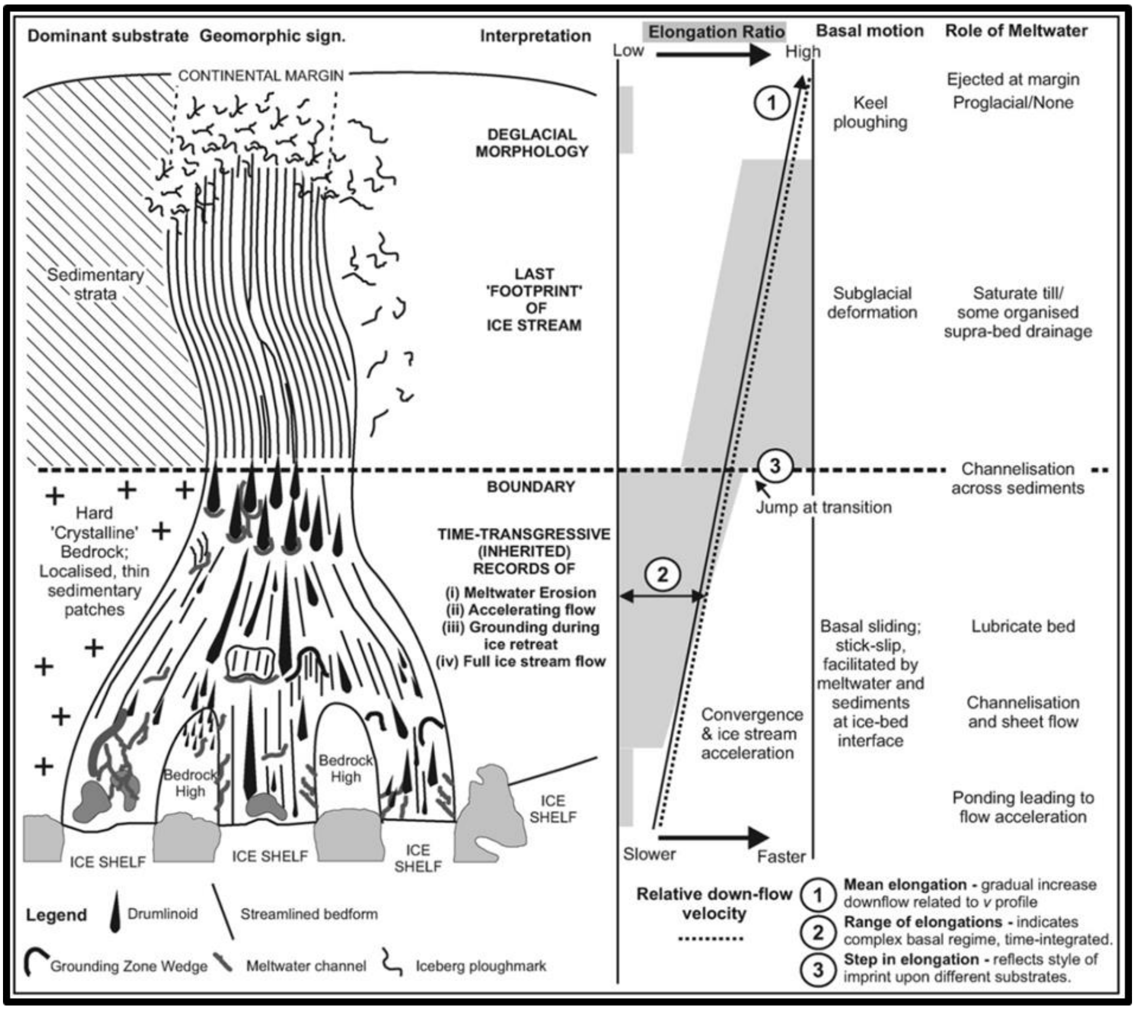

Figure 2.9 - A model for palaeo-ice stream landforms on the West Antarctic continental shelf. This schematic illustrates the landsystem assemblages interpreted, the velocity inferred, the role of meltwater and bedform elongation (Graham et al., 2009).

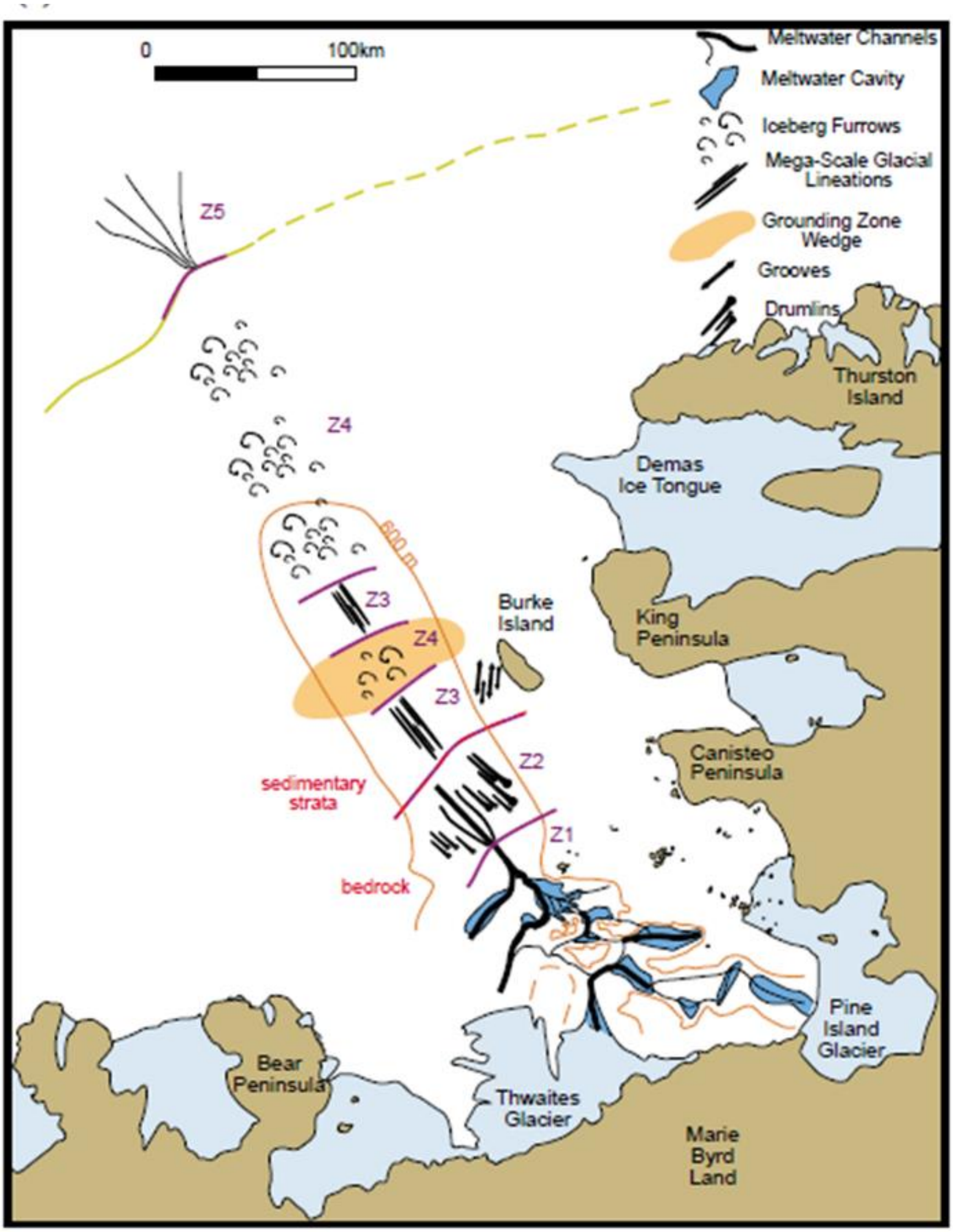

Figure 2.10 - Ice stream bedforms found in Pine Island Bay. The streamlined bedforms; mega scale glacial lineations and drumlins are clearly visible on both hard and soft bed sections of the ice stream (Lowe and Anderson, 2002).

As mentioned earlier, the subglacial bedforms produced from the contrasting processes occurring over soft and hard beds are different. A benefit of using erosional bedforms, found on hard beds or indeed mixed beds, to reconstruct ice dynamics and analyse basal conditions is that they have a high preservation potential, however, these bedforms are modified with each glacial cycle which means reconstructions of ice dynamics and basal conditions from a single phase, can be problematic. It should also be noted that the mechanisms responsible for bedrock bedform formation are not as well understood as soft bedded landfroms, which can complicate palaeo- ice stream reconstructions (Roberts and long 2005), however, it is clear that they differ from those that form drift bedforms. The setting of the Firth of Forth, which is surrounded on three sides by mountainous terrain that formerly harboured ice dispersal centres; the low lying coastal plain underlain by soft sedimentary rock and dissected by volcanic intrusions; plus the offshore depo-centre of the North Sea to the east; is a setting that may have provided ideal conditions for the development of mixed-bed ice stream imprint. Only a small part of this former ice stream has previously been investigated (Golledge and Stoker, 2006), but no systematic appraisal of its bedform assemblage/imprint has been undertaken.

2.5. Summary

As discussed in this chapter, ice streams can be classified as having either soft, hard or mixed beds. Moreover, there are different landforms produced according to whether the bed is soft or hard and most of the studies of palaeo-ice streams have tended to focus on soft bedded ice streams. Drumlins, MSGLs, shear margin moraines and ribbed moraines are all common and found on soft bedded ice streams. Roches moutonnées, whalebacks, bedrock megagrooves and crag-and-tails are found on hard bedded ice streams. Mixed bedded ice stream have been studied much less than soft and hard bed ice streams. These ice streams exhibit a mix of the characteristics identified on soft and hard beds. Numerous palaeo-ice streams around Antarctica have hard bedded onset zones with mixed bed trunks (Livingstone *et al.,* 2012). Palaeo-ice streams with a mixed bed all the way along the system, however, is much rarer. In relation to this thesis, the Firth of Forth is expected to be characterised by a mixed bed but no former systematic assessment of this ice stream has been undertaken. An analysis of both soft- and hard-bedded bedforms of the Firth of Forth, should give a comprehensive reconstruction of past ice stream dynamics in the area.

Chapter 3 – Study Area and Glacial History of the Firth of Forth

3.1 Introduction

This chapter will look at the study area and the glacial history of the Firth of Forth in more detail. Section 3.2 looks at the topography of the area and Section 3.3 look at bedrock geology. Section 3.4 will review the glacial history of the Firth of Forth focussing on deglaciation of the area (Section 3.4.1) and any published evidence of ice stream activity in the area (Section 3.4.2).

3.2. Topography

The study area (Fig 3.1) spans the length of the Highland Boundary Fault in the north and west, to the North Sea coast in the east, and down to Clydesdale and the River Tweed in the south. It displays an abundance of glacial landforms. This area is known as the Central Lowlands or Midland Valley. The Highland Boundary Fault is a major fault zone that runs from Arran, which lies to the south west of the study area, to Stonehaven in the north east of the study area. It is on the border of a topographic change, separating the Highlands and the Lowlands. The study region, therefore, generally consists of low lying plains such as Strathmore in the north east and Clydesdale in the south, but is interspersed with hills such the Ochil Hills and Campsie Fells. The two largest hills - the Pentland Hills and Lammermuir Hills - are in the south of the study area. The area has two large sea bays (the Firth of Forth and the Firth of Tay). The bedrock geology of the area is varied (Fig 3.2) and the vast majority of the lowland areas are covered in overlying drift, which gives a smoother topography (Fig 3.3).

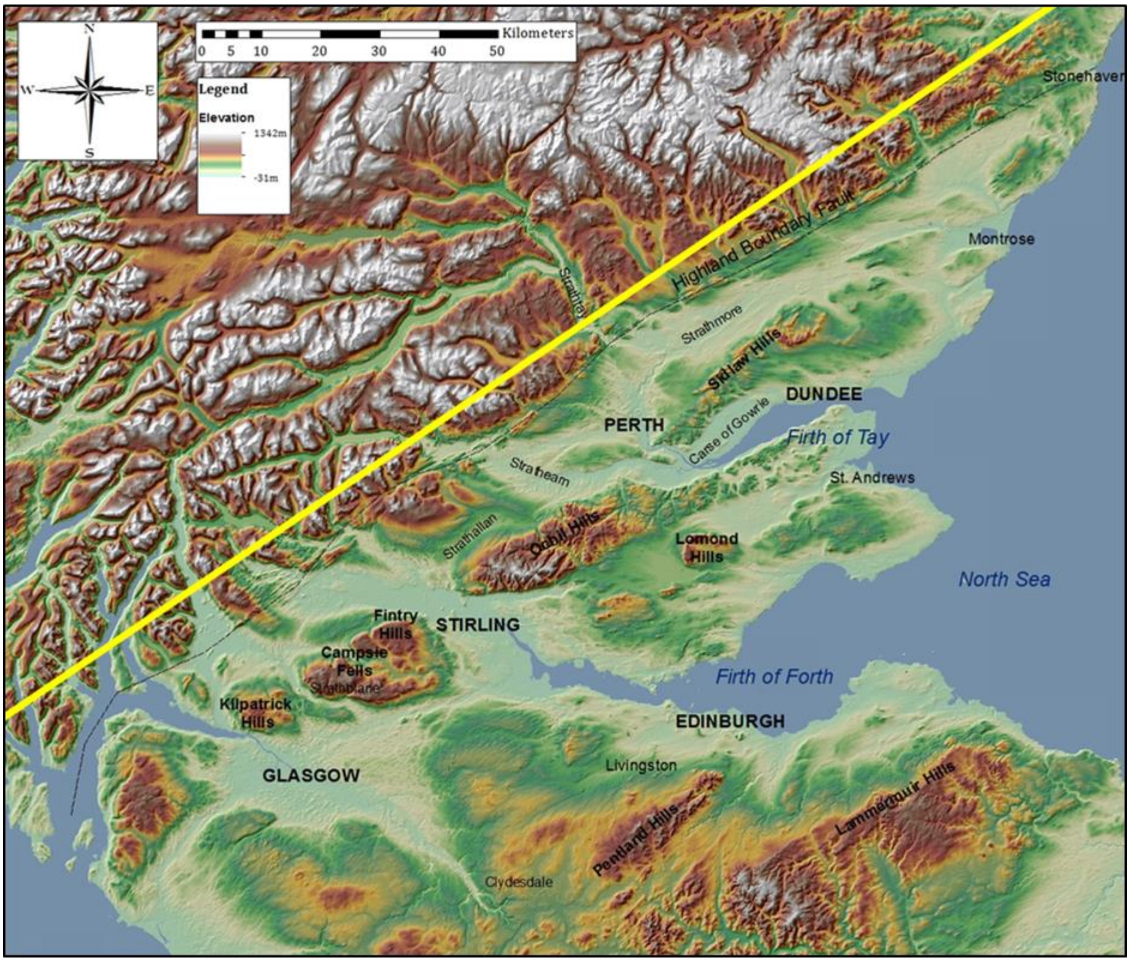

Figure 3.1 - The study area. Yellow line shows limits of mapping. It spans the length of the Highland Boundary Fault in the north and west to the North Sea coast in the east and down to Clydesdale and the River Tweed in the south. This area is known as the Central Lowlands or Midland Valley.

3.3 Bedrock Geology

A map of bedrock geology of the area shows that the northern section of the study area is predominantly sandstone with subordinate conglomerate, siltstone and mudstone which is fairly soft (BGS) (Fig. 3.2). This soft rock runs parallel to the highland boundary fault and covers Strathmore, Strathearn and Strathallan. This large area is bordered by smaller sections of mafic rock and mafic tuff which is harder rock as it contains iron and magnesium. This rock makes up the Sidlaw Hills, Ochil Hills, Fintry Hills, Campsie Fells and Kilpatrick Hills. It is also found in the upland areas in the south west of the study area and parts of the Pentland Hills. The Lomond Hills, Pentland Hills and Lammermuir Hills are topped with sandstone, siltstone and mudstone. The majority of the Lammermuir hills are made up of Wacke which is a sedimentary rock made up of a strong matrix of sand and clay and is a hard rock. The area around the Lomond Hills and Campsie Fells is sedimentary rock belonging to the Clackmannan group. This is a group of rocks comprised of coarse sandstone, siltstone, mudstone and limestone with thin coals and ironstones. Mafic, igneous, intrusive rock is found in small areas across the whole of the study area. Some of this bedrock geology is overlain with drift. The study area is predominantly lowland and so most of it is covered with overlying drift (Fig 3.3). The only sections of the study area not covered are the tops of the hills.

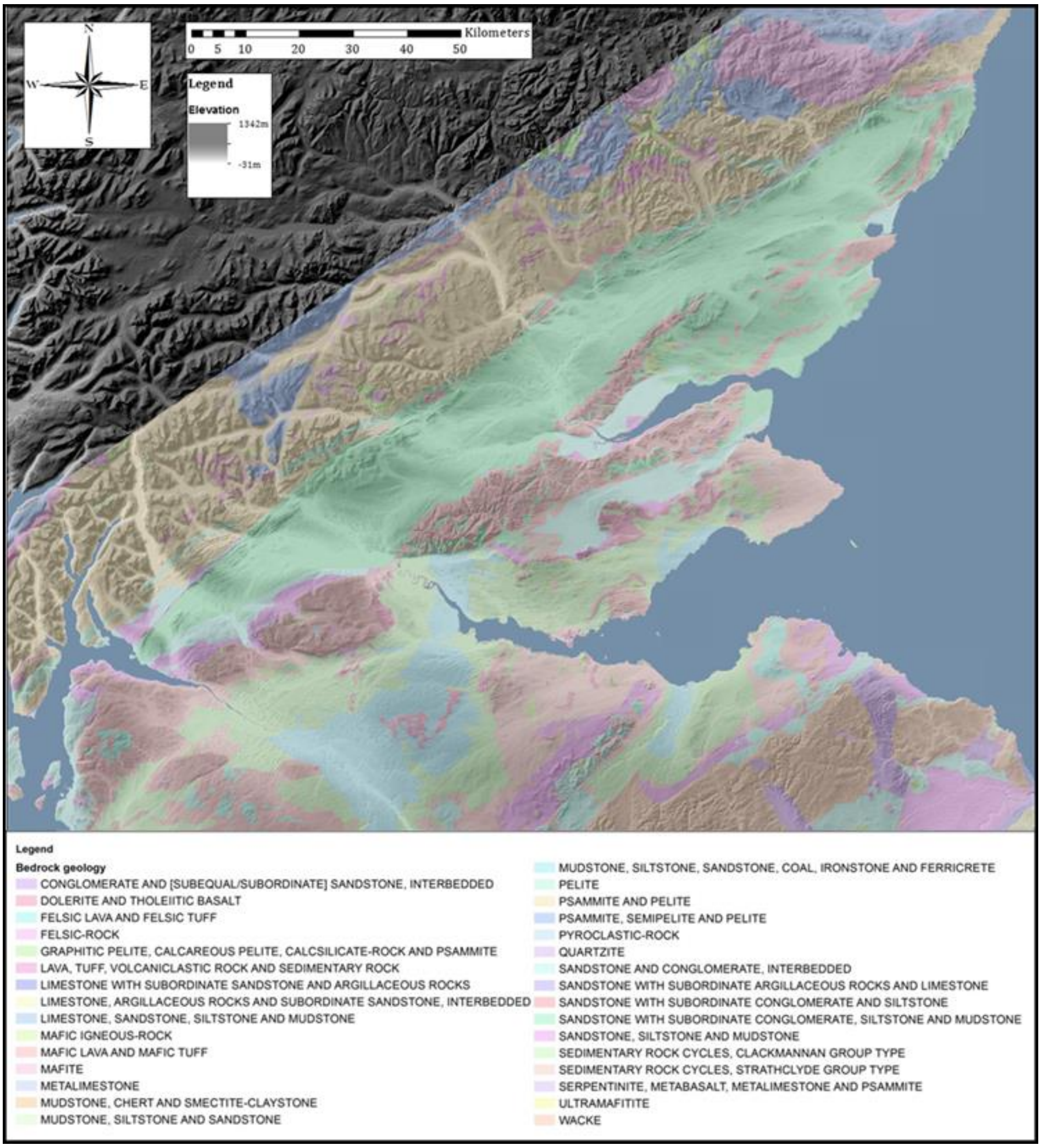

Figure 3.2 - Bedrock geology found in the study area. This information was obtained from the British Geological Survey.

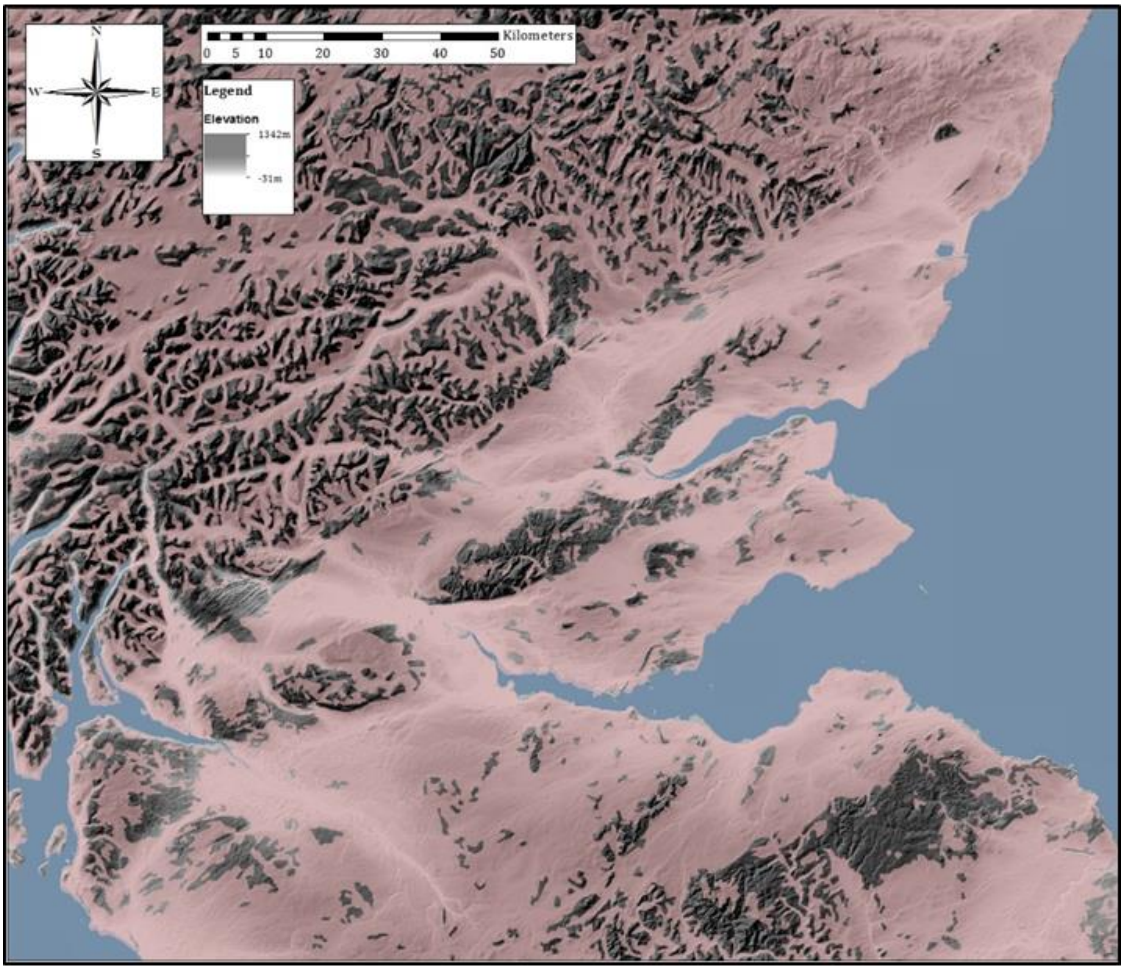

Figure 3.3 – The extent of overlying drift found in the study area. The drift covered areas are pink. This information was obtained from the British Geological Survey.

3.4. Glacial History of the Firth of Forth

A number of published studies over the years have analysed different sources and offered various dates for deglaciation in and around the area of the Firth of Forth. Some studies focus on locations near to the Forth, with ice streams that also feed the North Sea, such as the Tyne (to the south of the Forth; Bishop and Coope, 1977; Livingstone, 2015), the Tay (north of the Forth; Peacock, 2003) and the Stainmore (south of the Forth; Wilson *et al*., 2012). No studies so far focus solely on the Firth of Forth area, although some include it in their mapping and analysis of the BIIS and some suggest that a palaeo-ice stream once existed there. This section examines the evidence of research that identifies a pattern of deglaciation and ice stream activity in North East Britain, around the North Sea. It will look firstly at the BIIS as a whole, then analyse areas north and south of the Forth more closely before finishing with the implications of this on the deglaciation of North East Britain. Then it will look at the evidence that has been published so far of an ice stream in the Firth of Forth.

3.4.1 North Sea deglaciation

Establishing a glacial chronology is important for any palaeoglaciological reconstruction. It is also important to retreat rates and ice sheet dynamics such as ice streaming. Clark *et al.* (2012) reconstructed the deglaciation of the BIIS, they found that the BIIS was made up of a shelf-parallel configuration from SW Ireland to NE Scotland. The ice sheet retreated into a number of separate ice caps as opposed to retreating as a single mass. Rates of ice loss varied over space and time. The central area of the BIIS, covering the Southern Uplands and northern Pennines, consisted of cold-based plateau ice caps intersected by four major terrestrial ice streams (Forth, Tweed, Tyne and Stainmore) (Fig 3.4) draining eastward (Livingstone *et al*., 2015), but they have not been systematically mapped and analysed.

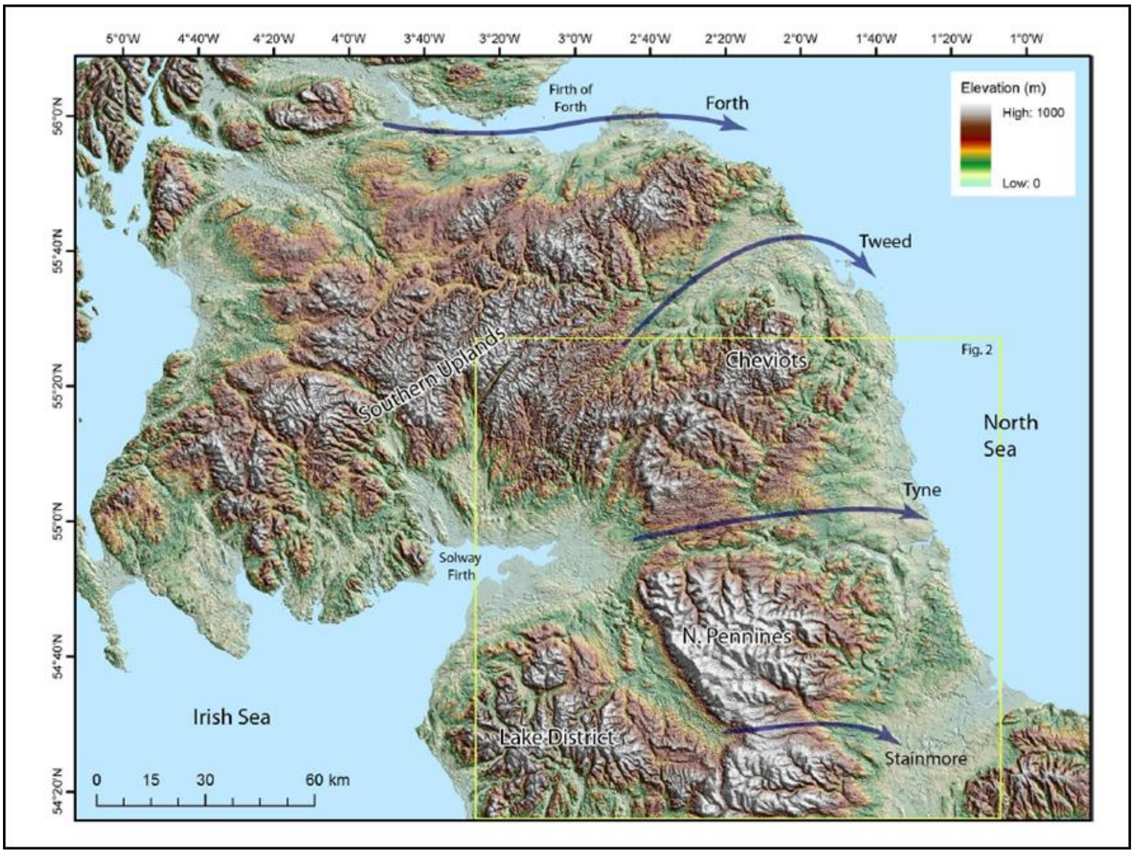

Figure 3.4 - NEXTMap image illustrating the complex topography of northern England and southern Scotland. The four mayor palaeo-ice stream corridors (Forth, Tweed, Tyne and Stainmore) are highlighted by dark blue arrows (Livingstone *et al*., 2015).

Clark *et al.* (2012) reported the chronology of retreat of the BIIS and claimed that during the last glacial period, the BIIS reached its maximum extent around 27 ka BP (Fig 3.5). Table 3.1 summarises the chronology of retreat reported in Clark *et al.* (2012).

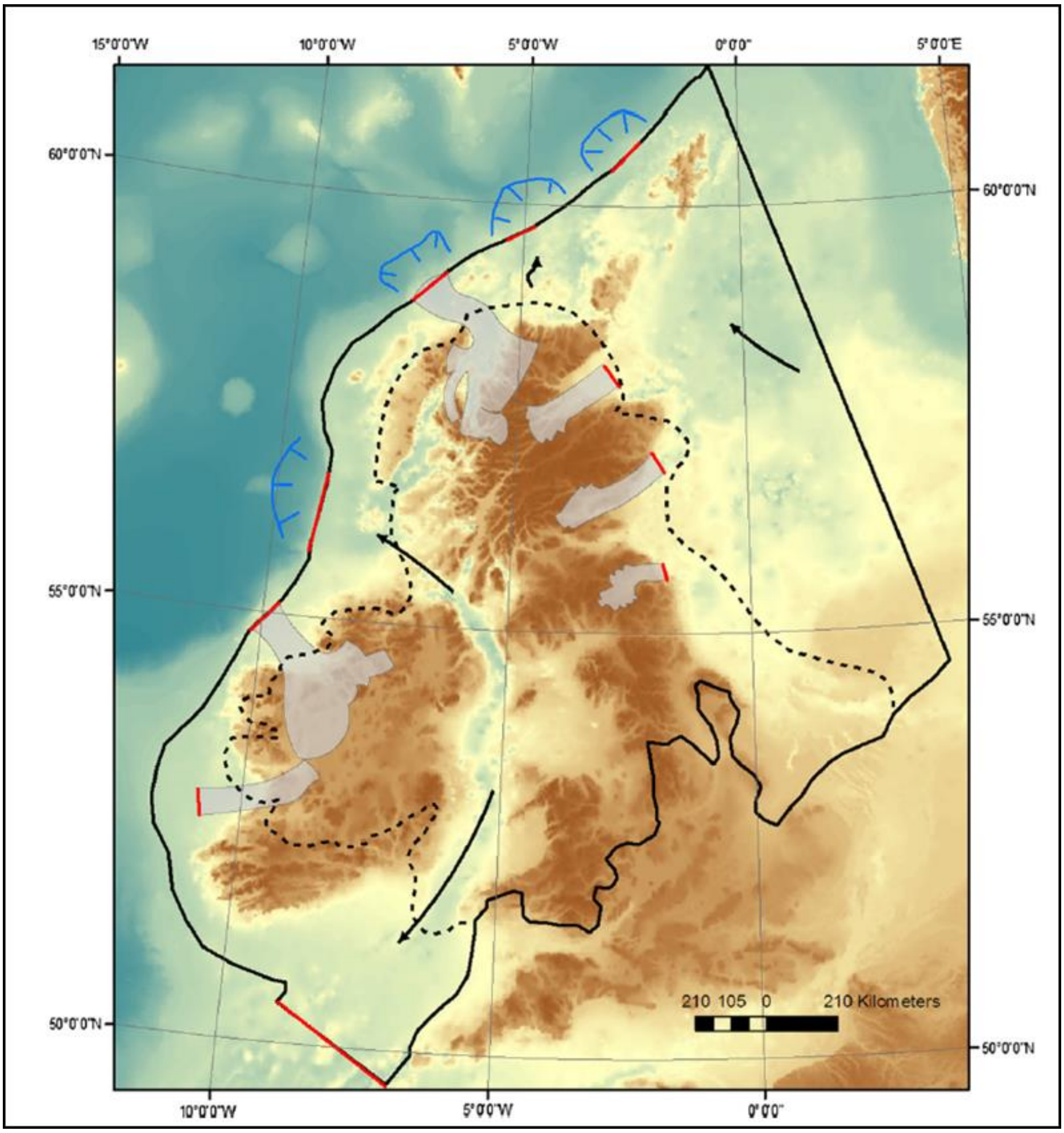

Figure 3.5 - Two end-member reconstructions of maximum extent of the British-Irish Ice sheet. The dashed is the traditional view. The solid line includes complete ice cover of Ireland and Scotland (Clark *et al.*, 2010).

Table 3.1 - This summarises the chronology of retreat found by Clark et al (2012).

23ka BP	• Ice withdrew along northern boundaries • Southern margins expanding • Transient ice streaming down Irish Sea • Lobes advance in Cheshire Basin, Vale of York and east coast of England • Ice divides migrated south
19ka BP	• Widespread marine-based ice loss • Particular ice loss in northern North Sea and Irish Sea • Considerable dynamic-thinning
17ka BP	• Final collapse of all marine sectors • Most margins beginning to back-step onshore • Disintegration of the North Sea 'ice bridge' between Britain and Norway loosely constrained in time – possibility of catastrophic collapse of this sector highlighted
16ka BP	• North Channel and Irish Sea ice streams split ice sheet into separate Irish and Scottish Ice sheets.

Various publications have suggested retreat dates for parts of North East Britain north and south of the Firth of Forth study area. To the south of the study area is the Tyne and Stainmore, both of which feed the North Sea. In 1977, Bishop and Coope analysed a basal peat unit, west of the Tyne Gap, in the Solway Lowlands which is just south of the Firth of Forth. They offered a minimum age for ice free conditions of 14.3±0.4 ka BP. However, Livingstone *et al*. (2015) reconstructed the pattern of the Tyne Gap ice stream (south of the Firth of Forth) and constrain the timing of its retreat. They concluded that retreat in the area began 18.7-17.1 ka and the area become ice free before 16.4-15.7 ka. Wilson *et al*. (2012) suggested that the Stainmore area was deglaciated by ~17 ka BP after obtaining ^{10}B surface exposure ages on Sharp granite erratics, west of the Stainmore Ice Stream in the Vale of Eden.

To the north of the study area is the Tay. In 2003, Peacock examined Late Devensian marine deposits (Errol Clay Formation) at the Gallowflat Claypit in eastern Scotland, just north of the Firth of Forth. He concluded that deglaciation of the middle Tay estuary occurred between 14.5 and 14 ka BP following the recession of the Tay-Forth glacier from its advance Late Devension position at the Wee Bankie Terminal Moraine. McCabe *et al*. (2007) provided a revised deglacial chronology for east-central Scotland using new ^{14}C dates. They obtained data from monospecific samples of the foram *Elphidium clavatum.* They stated that the initial deglaciation of Scotland actually occurred before 17 720 ± 50 ^{14}C years bp. All of these publications provide dates of deglaciation for North East Britain in areas north and south of the Firth of Forth.

Roberts *et al* (submitted) analysed the imprint of the North Sea Lobe. They found, using new radiocarbon dates, that the area offshore the coasts of

Durham and Northumberland retreated between 19.9 ka and 16.5 ka. They state that it is likely that the North Sea lobe was fed by ice through the Firth of Forth. They concluded that ice flux through the Forth Ice Stream onset zone was one of the dominant controls on the rate of retreat of the North Sea Lobe.

3.4.2 Evidence of an ice stream at the Firth of Forth

In 2006, Golledge and Stoker confirmed the existence of the Strathmore ice stream, in the north of the study area. They used both marine and terrestrial subglacial landforms to reconstruct ice flow patterns the area. They concluded that the Strathmore ice stream spanned an area of 100 km in length and 45 km wide. By 2008, Bradwell *et al*. stated that an ice stream 'probably occupied' the Firth of Forth area and the surrounding lowlands, but little detailed mapping has been undertaken and nothing has been formally identified as a palaeo-ice stream track. They also noted that marginal retreat of the British Ice Sheet could have been quite rapid in the area of the Firth of Forth due to ice stream activity. This was further corroborated in 2009 when numerical ice sheet modelling by Hubbard *et al*. (2009) highlighted an ice stream at the Firth of Forth.

In 2010, Hughes *et al*. mapped over 39,000 subglacial landforms of the last British Ice Sheet. They identified some landforms in the Firth of Forth region and classified these as drumlins and crag-and-tails. They found that, in general, drumlin lengths were evenly distributed across the country, but they noticed a cluster of long drumlins (>2 km) in the Forth region. They also noted an apparent topographic control on drumlin distribution in the Forth area, whereby drumlins appear to deflect around the Pentland and Lammermuir Hills. They identified numerous crag-and-tails in the area within and adjacent to drumlin fields. It should also be noted that whilst Hughes *et al*. (2010) mapped a large number of drumlin forms in the Firth of Forth area, they did not report other soft bed forms such as MSGLs. Although this map provided a good overview of subglacial bedforms across the whole of Britain, it was not within the scope of that study to explore upstream/downstream ice stream bedform changes or explore the transitions between hard and soft beds.

Chapter 4 – Methodology

4.1 Introduction

This chapter is split into two parts. The first part (Section 4.2) explains the methods used to undertake geomorphological mapping; remote sensing image acquisition (Section 4.2.1) and glacial geomorphological mapping and analysis techniques (Section 4.2.2). The second part (Section 4.3) details the methods used to produce a palaeo-glaciological reconstruction from the mapped data; flow-sets (Section 4.3.1) and linking flow-sets to an ice margin chronology (Section 4.3.2).

4.2 Geomorphological mapping methods

There have been a number of different methods used to undertake geomorphological mapping in the past and these include mapping from satellite imagery (Smith *et al.*, 2006; Storrar and Stokes, 2007; Livingstone *et al.*, 2008) and mapping from airborne imagery (Evans *et al.*, 2006; 2007). This section will discuss this approach and then elaborate on the methods used in this research.

4.2.1 Remote sensing image acquisition

A wide range of earth sciences have utilised landform mapping as a primary data collection method. These include hydrology (Hooke *et al.*, 1994) and geology (Gold *et al.*, 1973). These subject areas aim to understand processes operating in particular environments and that require the visualisation of surface morphology. Traditionally, landforms were mapped in the field, but it is now possible to map larger areas in a much shorter time frame due to advances in remote sensing technologies (Clark, 1994).

Remote sensing is the science of acquiring information about an area without making physical contact with it. It has transformed glacial geomorphological mapping, particularly in relation to our knowledge and understanding of palaeo-ice sheets (Clark, 1994; Jansson and Glasser, 2005; Smith and Knight, 2011). Remote sensing also allows investigations beyond the spectral range of human perception (i.e. beyond the visible range of the electromagnetic spectrum). There is a wealth of remote sensing products available from both air- and space-borne technology. Derived products such as digital elevation models (DEMs) can be used to map landforms as they directly represent surface elevation. Over the last two decades, the use of DEMs had increased as a result of national mapping programmes which produce DEMs from contour data and aerial photography (Smith and Clark, 2005). The Landmap project (Kitmitto *et al*., 2000) provides complete DEM coverage of the UK and Ireland and the Shuttle Radar Topography Mission (SRTM; Rabus *et al*., 2003) provides almost global coverage meaning that DEMs are a valuable resource for landform researchers.

This research was undertaken using NEXTMap imagery. This elevation data is collected using airborne Interferometric Synthetic Aperture Radar (IFSAR) technology, which allows for large areas to be covered rapidly at high spatial resolutions. This research utilises the Digital Terrain Model (DTM), with a 5 m vertical resolution, which removes trees, vegetation and human structures and represents the underlying terrain as a smoothed surface. These data were imported into ArcGIS 10.0 for manipulation and visualisation. Mapping was conducted by on-screen digitisation of features. The features were mapped as either lines or polygons (see 4.2.2). The different features were digitised on separate layers after visual interpretation and stored as shapefiles. The featured were identified by adjusting the hill-shade relief on the models and by viewing them from different sun angles and elevations, following recommendations in Smith and Clark (2005).

4.2.2 Glacial geomorphological mapping and analysis

Individual landforms were identified, categorised and digitised manually on-screen in ArcMap 10.0, using the Study Area defined in Fig. 3.1. Preliminary mapping led to the identification of five categories of landform. Each landform type was digitised in a separate shapefile as either a polyline or polygon. Table 4.1 details the process of landform identification.

Table 4.1 - Rules used to identify and classify the landforms in the study area.

Name	Identification criteria	Shape
Flow traces	• Low amplitude • Ridges of drift • Lineations • Unable to draw around break of slope	
Drumlins	• Ridges of drift • No bedrock at surface • Break of slope clearly visible	
Intermediate Forms	• Ridge of soft sediment • Bedrock clear at surface • Break of slope clearly visible	
Crag-and-Tails	• Bedrock with drift tail • Drift tail at least 2x length of bedrock crag	
Streamlined Bedrock Ridges	• Ridge of streamlined bedrock • No soft sediment visible • Low amplitude	

Flow traces were digitised as polylines. They were identified as low amplitude, ridges of drift with no bedrock. They were clear lineations but with no obvious break of slope to draw around. Drumlins were digitised as polygons. They were identified as smooth ridges of drift with no bedrock visible at the surface and with a generally oval or tear-drop shaped planform. They had a clearly visible break of slope that could be drawn around. Intermediate forms were digitised as polygons and were used to represent landforms that were intermediate in appearance between drumlins and classic crag-and-tails. They were identified as ridges of soft sediment with some bedrock visible at the surface, but not always at the stoss side and not always as obvious as crag-and-tails. Crag-and-tails were digitised as polygons. They were identified as bedrock at the surface at the stoss-side with a drift tail in the lee-side that generally tapered down-ice. The drift tail had to be at least two times the length of the bedrock to be classified as a crag-and-tail. Finally, streamlined bedrock ridges were digitised as polylines. They were identified as a low amplitude ridge of bedrock with a generally ‘rougher’ appearance and with no soft sediment visible.

The bedrock forms identified were analysed by measuring their size, elongation ratio and density in order to identify any spatial patterns, (e.g. Roberts and Long (2005), Eyles (2012) and Eyles and Putkinen (2014) (Table 4.2).

Table 4.2 This table summarises general patterns found in bedrock forms identified by Roberts and Long (2005), Eyles (2012) and Eyles and Putkinen (2014). These criteria were used to analyse the bedrock forms identified in the study area.

Low elongation ratio (<5:1)
High bedform density (> 200km^2)
Macro RMs (>100m long)
Small WB and RM superimposed on upper surfaces forming multi-swale complexes
Large-scale drumlinized and megagrooved bedrock surfaces extending tens or hundreds of km.
Megalineated bedrock terrain in upstream onset zones
Streamlined promontories
Rock drumlins (bullet shaped streamlined rock)
Orientation of rock drumlins independent of bedrock structures and joints.
Megaflutes and megagrooves. Elongate bedrock flutes and grooves (tens of m wide and >1km long)

Once the landforms were identified and digitised, data containing information about each landform were extracted from ArcGIS to allow an analysis of landform morphometry. Ultimately, length, width, elongation ratio and orientation data were desired for each landform. For landforms mapped as polylines (flow traces and streamlined bedrock ridges) only length and orientation data can be collected automatically. The lengths of polylines are automatically calculated in ArcGIS so this data was easily extracted. Area and perimeter data for polygons are automatically calculated and it is possible to approximate the length and width of each feature from these numbers (see Clark *et al*., 2009). In their study of drumlin size and characteristics, Clark *et al*. (2009) approximated drumlin length and width based on the formula for an ellipse. The formulae they used and used in this research is as follows:

$$L = \frac{1}{\pi}\sqrt{P^2 + \sqrt{P^4} - 16\pi^2 A^2}$$

$$W = \frac{1}{\pi}\sqrt{P^2 - \sqrt{P^4} - 16\pi^2 A^2}$$

where L = length, W = width, P = perimeter and A = area. Elongation ratio is then calculated by dividing the length by the width.

Orientation data were also acquired differently for polylines and polygons. For polylines, a function of the ‘Add-In’ called ‘easy calculate’ was used. This gave the orientation of the line based on the direction in which it was digitised. This produced the correct information in most cases; however, some needed to be changed manually if they were digitised in the opposite direction to ice flow. This was usually obvious because ice flow through the area is known to be broadly from west to east (Clark *et al*., 2012). The polygon orientation data were acquired using the minimum bounding geometry tool. This calculated the orientation of the imagined long axis connecting the antipodal pairs of an ellipse.

4.3 Palaeoglaciological Reconstruction

4.3.1 Flow-sets

The concept of flow-sets was first introduced by Boulton and Clark (1990). Flow-sets are coherent groups of landforms follow a coherent and systematic pattern and they can be interpreted to record distinct phases of ice flow (Clark, 1993). Flow-sets are identified by examining the spatial arrangement of bedforms, their morphometry and their orientation. Patterns of flow-sets are useful to reconstruct ice flow direction (Boulton and Clark, 1990) and the flow-sets can also be linked to specific ice dynamics (Kleman *et al*., 2006).

Once the landforms were identified, categorised and digitised, the raw data was grouped into flow-sets using criteria set out by Clark (1999) (Figure 4.1). In order to be categorised as a flow-set the landforms within each flow-set needed to have a similar orientation to its neighbours, be closely packed with its neighbours and display similar morphemetry to its neighbours (Figure 4.2; Clark, 1999). The interpretation of potential ice stream flow-sets from fragmented and overprinted landforms records in the study area is difficult. It is assumed that flow-sets that formed under different conditions have different geomorphological signatures (Kleman *et al.*, 2006). Kleman *et al*., (2006) outlines four types of flow-sets; wet-based deglacial, frozen-bed deglacial, ice stream and event. The flow-sets in this study will be classified in this way. Warm-based deglacial flow-sets are defined as having ice flow traces such as drumlins and flow traces with superimposed, aligned eskers. Cold-based deglaciation flow-sets only contain a pattern of meltwater features superimposed on old glacial or non-glacial surfaces. Event flow-sets contain lots of ice flow traces but lack eskers and moraines. Ice stream flow-sets contain mega-scale glacial lineations, convergent ice flow patterns and other criteria indicative of ice stream activity. These criteria are dependent upon whether the bed is hard or soft.

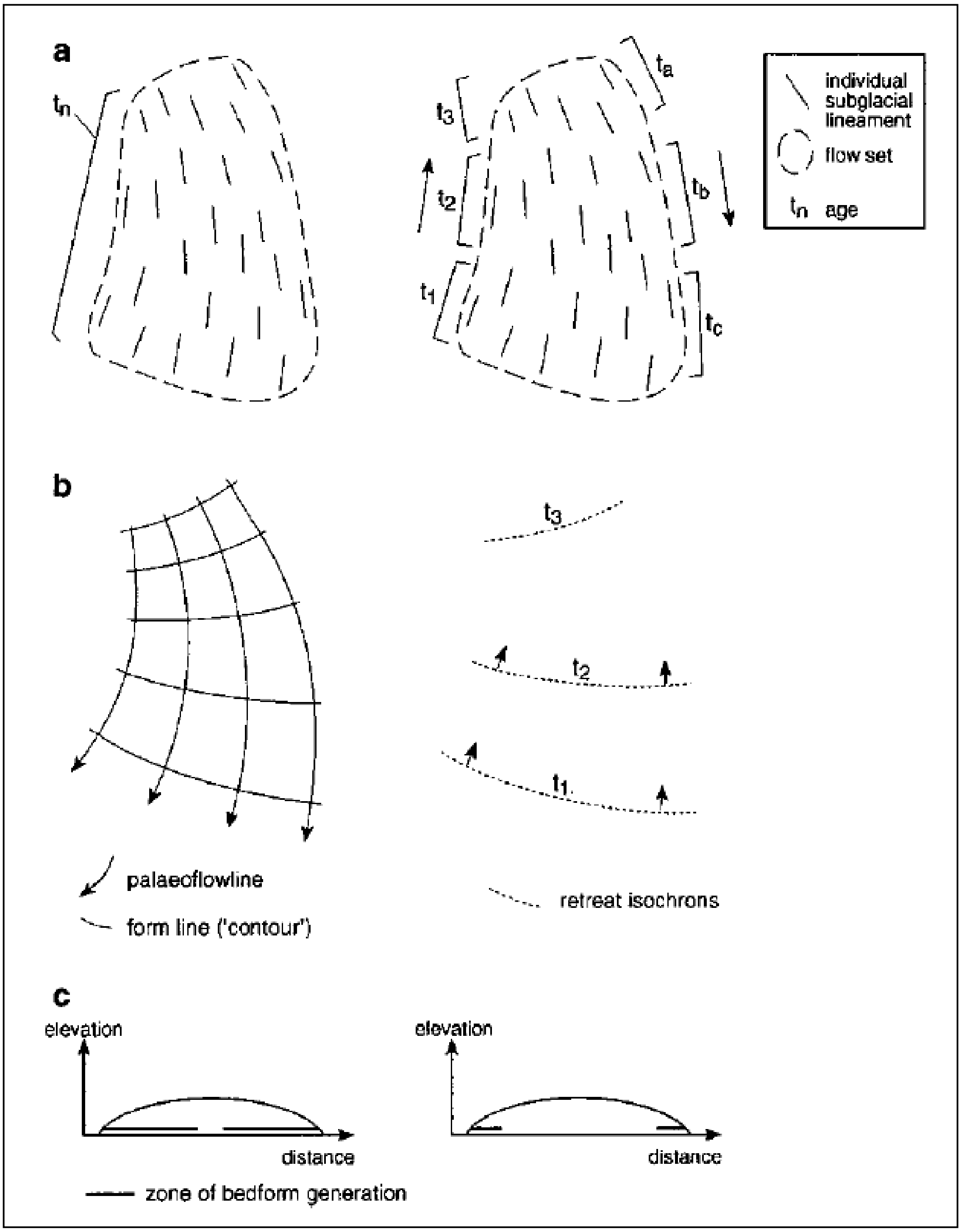

Figure 4.1 - (a) Flow-set of subglacial drift lineations that may have formed isochronously at time t_n, or time-transgressively from t_1 - t_3 or t_a - t_c. (b) Alternative modes of interpretation of such a pattern. © Consequent presumptions about glaciodynamic context, as either along extensive palaeo-flowlines or restricted to submarginal positions (Clark, 1999).

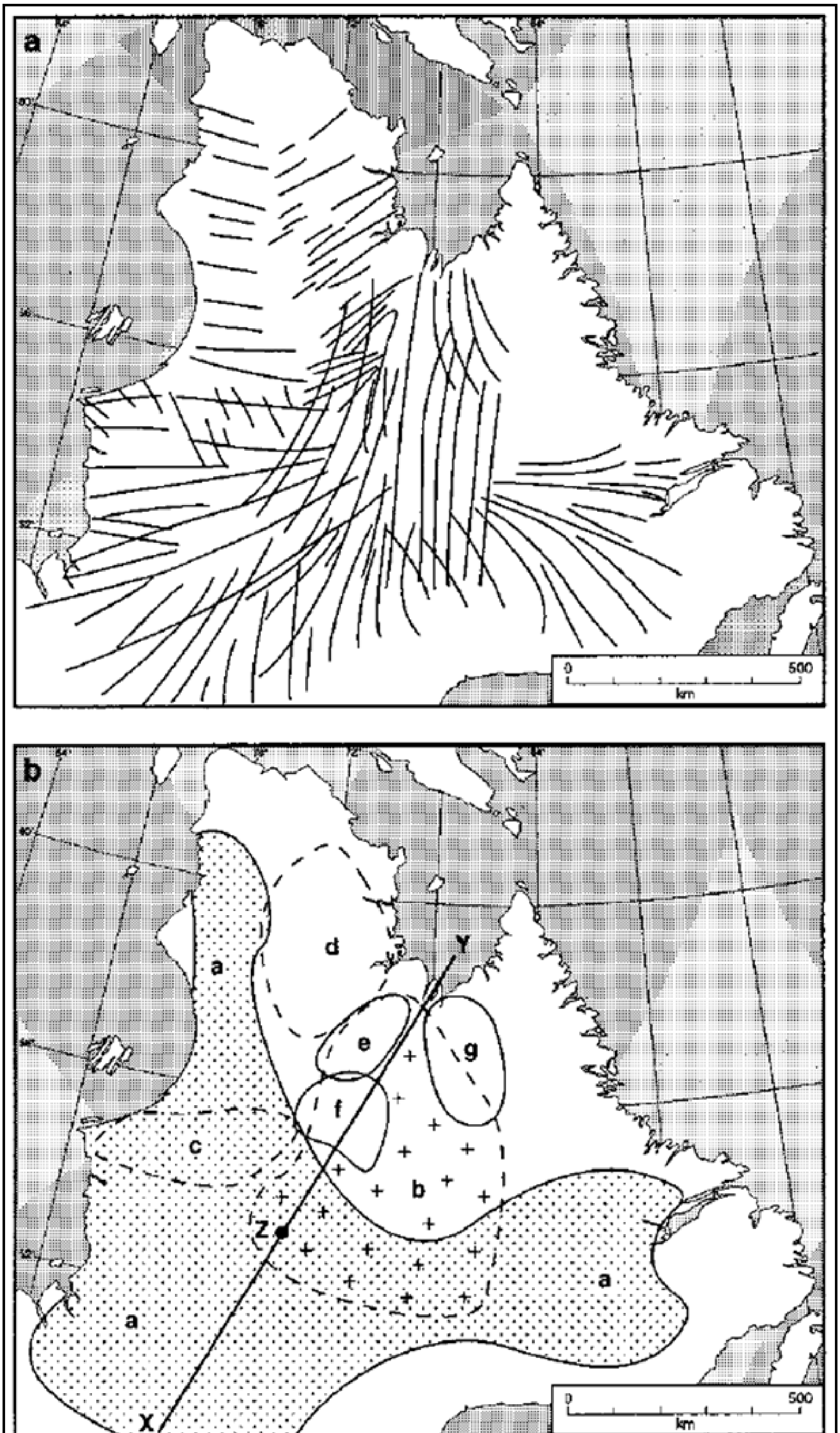

Figure 4.2 - An example of how subglacial lineations are grouped into flow sets. (a) Subglacial drift lineations of Quebec-Labrador, summarised into flow sets. (b) Flow-sets subjectively identified using criteria (Clark,1999).

Following their identification as a specific ice flow event, each flow-set was then examined to look for specific criteria of ice streaming set out in a variety of papers reporting both hard- and soft-bedded ice streams (Stokes and Clark, 1999; Clark and Stokes, 2005; Roberts and Long, 2005; Eyles, 2012; Eyles and Putkinen, 2014). Each of these criteria are discussed below.

Stokes and Clark (1999) and Clark and Stokes (2005) identified a distinctive set of geomorphological criteria for identifying soft bedded palaeo-ice streams based on the characteristic of contemporary ice streams and conventional glacial geomorphology theories (Table 2.1). Each flow-set identified was examined to determine to what extent they fit these criteria. Each aspect of their criteria, set out in Table 2.1, was considered when examining the different flow-sets. The first characteristic set out by Stokes and Clark (1999) and Clark and Stokes (2005) is that ice streams have specific shapes and dimensions with lengths of over 150 km and widths of over 20 km. The size of the study area was examined as it is expected that a palaeo-ice stream should be a similar scale to modern ice streams (>20km wide and >150 km long). It is expected that former ice stream beds should display subglacial bedforms that converge, forming an onset zone, into a narrower trunk. The flow-sets were therefore analysed to determine to what extent they exhibit these characteristic converging patterns.

Ice streams are also expected to have a sharply delineated margin consisting of abrupt lateral margins and the presence of shear margin moraines (see Literature review 2.2.3; Stokes and Clark,1999; Clark and Stokes, 2005). Abrupt lateral margins are a common feature of ice streams, caused by the sudden change from fast to slow flowing ice. It is expected that palaeo-ice stream beds will display a sharp zonation of subglacial bedforms at their margin with a sudden discontinuation of the bedform compactness found in the track. Shear margin moraines may form as a result of sediment accumulation at the margin caused by increased water at the margin (Stokes and Clark, 2002). The margins of the ice stream were scrutinised to determine if any of these landforms are present.

Highly attenuated bedforms are an indication of high velocity (see literature review 2.2.1 and 2.2.2; Stokes and Clark, 1999; Clark and Stokes, 2005). These were analysed through the calculation of the elongation ratio which is simply the length divided by the width. Although somewhat arbitrary, Stokes and Clark (1999) and Clark and Stokes (2005) suggest that bedforms with an elongation ratio of > 10:1 indicate ice stream activity. It is also expected that ice streams follow a distinct velocity pattern.

As the study area extends from inland to the coast, this study will evaluate the extent to which any ice stream extended offshore. In marine-terminating ice streams, the velocity of the ice stream increases from onset to the terminus (see literature review 2.2; Fig 2.1). There is also a higher velocity in the main trunk of the ice stream as opposed to at the marginal areas where there is a sudden decrease in velocity. The study area will therefore be analysed to determine if it exhibits the characteristics of a marine terminating ice stream. Finally, the accumulation of substantial sediment off shore may also suggest previous ice streaming activity. However, no offshore work was available for analysis for this investigation.

In terms of hard-bedded ice streams, Roberts and Long (2005), Eyles (2012) and Eyles and Putkinen (2014) investigated streamlined bedrock terrain of palaeo-ice streams (see literature review 2.3). Their findings are summarised in Table 4.2, which is an attempt to define some potential criteria for identifying a hard-bedded palaeo-ice stream. Large-scale meltwater channels, streamlined and drumlinized bedrock outcrops, and mega-groove/ridge features extending tens to hundreds of kilometres are features typical of a hard bed setting. Their presence is often coincident with ice stream onset zones (Lowe and Anderson; 2002; Bradwell and Stoker, 2015). Elongation ratios can vary widely. At the megascale megagrooves/ridges can be 10-100's of km long with ELR's in excess of 10:1. At the macro/meso/microscale rock drumlins or large.roche moutonnées can have ELR's < 5:1. Roberts and Long (2005) state that ice meso- to microscale bedrock bedforms often have low ELR's of less than 5:1 with a high density of bedforms in excess of 200 km$^{2.}$ This is likely a result of intense glacial erosion and superimposition. However, smaller landforms were not identified in this study due to the scale of the remote sensing limitations. Any landform < 5m in length is unlikely to be identified.

4.3.2 Linking Flow-sets to an Ice Margin Chronology

Once the flow-sets were identified and classified, four margin retreat positions for the Forth ice stream were projected using the flow-sets that were assumed to be active during each stage of deglaciation. These margin positions are based solely on the landform and flow set mapping undertaken during this study. They were hypothesised by embedding the flowsets behind the ice margins in an up-ice position to create a reconstruction of flow-set activity throughout deglaciation. The positions considered whether ice would have been constrained by topography and which flow sets would have been active at each position. The first position was projected as the full extent of ice cover and flow and that the ice flowed into the sea. This will therefore include the whole of the study area and flow-sets assumed to be active during this phase will be those that suggest ice flow that is not influenced by topography i.e. flow-sets that indicate ice was thick and flowed independent of topographical obstacles. The second position was based on ice having thinned and now constrained by topography. The flow-sets that flow independent of topography in phase one were switched off and those that flowed around the topographical obstacles and into the sea were switched on (Figure 4.3). The third and fourth positions are based on further thinning and only switches on flow-sets further inland that were topographically constrained. Dates were then estimated for each position using the dated retreat positions from Clark *et al*. (2012).

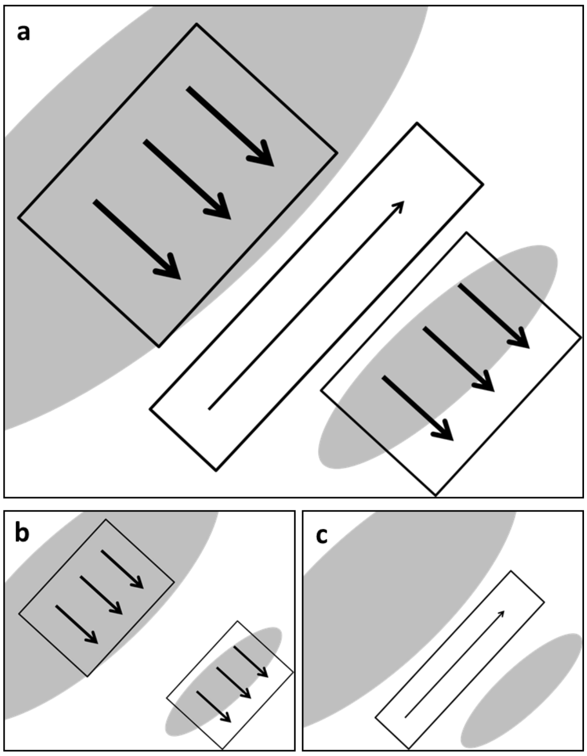

Figure 4.3 - Sketch to show how flow sets were constrained and not constrained by topography. (a) All flow sets in the location. (b) Flow sets not controlled by topography so assumed to be older and active during maximum extent. These flow sets are assumed to switch off during deglaciation. (c) Flow set controlled by topography assumed to be younger and active during a phase of deglaciation. This flow set was not active during maximum extent.

Chapter 5 – Results

5.1 Introduction

This chapter will outline the different types of landform mapped and will describe their distribution and relationship to other features, as well as their relationship with the topography, bedrock geology and overlying drift (Section 5.2). Five landform types have been identified (see Methods 4.2.2; Table 4.1): flow traces (Section 5.2.1), drumlins (Section 5.2.2), intermediate forms (Section 5.2.3), crag-and-tails (Section 5.2.4) and streamlined bedrock ridges (Section 5.2.5). It will then outline the flow sets identified and their use to determine ice margin chronology.

5.2 Bedform type and distribution

5.2.1 Flow traces

Flow traces were identified as a low amplitude ridge of drift where a clear break of slope was not visible (Figure 5.1). They were named flow traces because it was not initially clear if they had the characteristics of flutes or megaflutes. Boulton (1976) described flutes as bedforms composed of stratified sediment with dimensions of < 2 m high, < 3m wide and very long (up to 1 km). Rose (1987) categorised flutes as bedforms with lengths between 10 m and 100 m and megaflutes as bedforms with lengths of around 90 m to 1500 m. A break of slope is identifiable for flutes and megaflutes, but this is not the case with the flow traces identified in the study area. Thus, whilst they may be similar in morphometry to flutes and megaflutes, flow traces are much less obvious and we acknowledge greater uncertainty. A total of 256 flow traces were mapped across the study area (Fig. 5.2). The width of flow traces are not able to be measured because a clear break of slope is not visible. The lengths of the flow traces identified in the Firth of Forth area are between 330 m and 3,498 m, with a mean length of 1,413 m and a median length of 1,328 m. They therefore have characteristic composition and lengths of flutes and megaflutes.

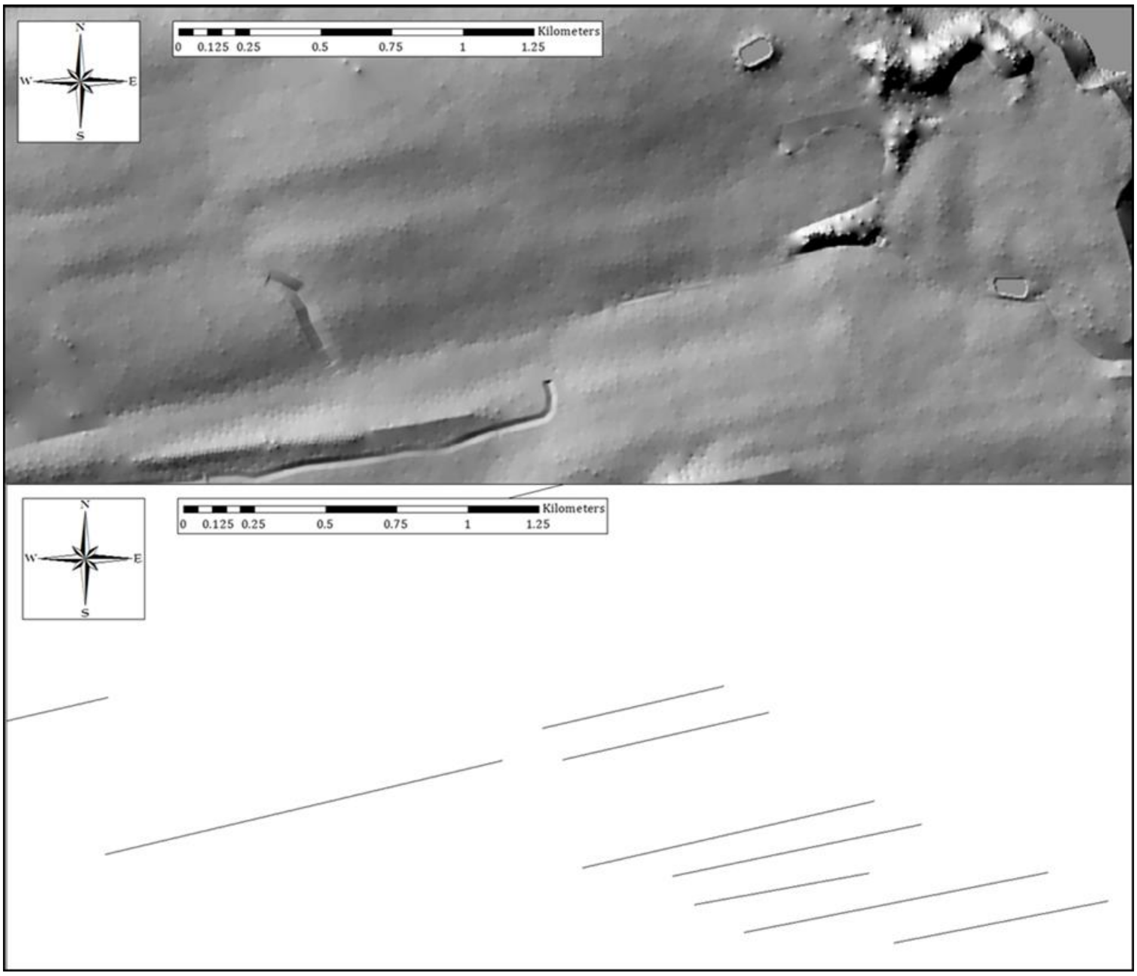

Figure 5.1 - Imagery of the flow traces identified. Flow traces were identified as a low amplitude ridge of drift where a clear break of slope was not visible. Top image is the NEXTMap DEM used and the bottom image is the digitised flow traces. Any other types of landforms mapped in this area have been left off this figure. Figure 5.2 shows their distribution throughout the study area.

Flow traces are evident in specific clusters in the Firth of Forth and cover a small area (Fig. 5.2). They generally have an easterly and north easterly orientation. The majority are located close to the east coast with only a few further inland. The largest cluster is east of Edinburgh which is the south east section of the study area (Figure 5.2; Figure 3.1). The majority of flow traces (32%) are found on sandstone with subordinate conglomerate, siltstone and mudstone. 30% are found on sedimentary rock cycles (Clackmannan group type, 14%, Strathclyde group type 16%) and 16% are found on mafic lava and mafic tuff. The other geology types contain either no flow traces or very few.

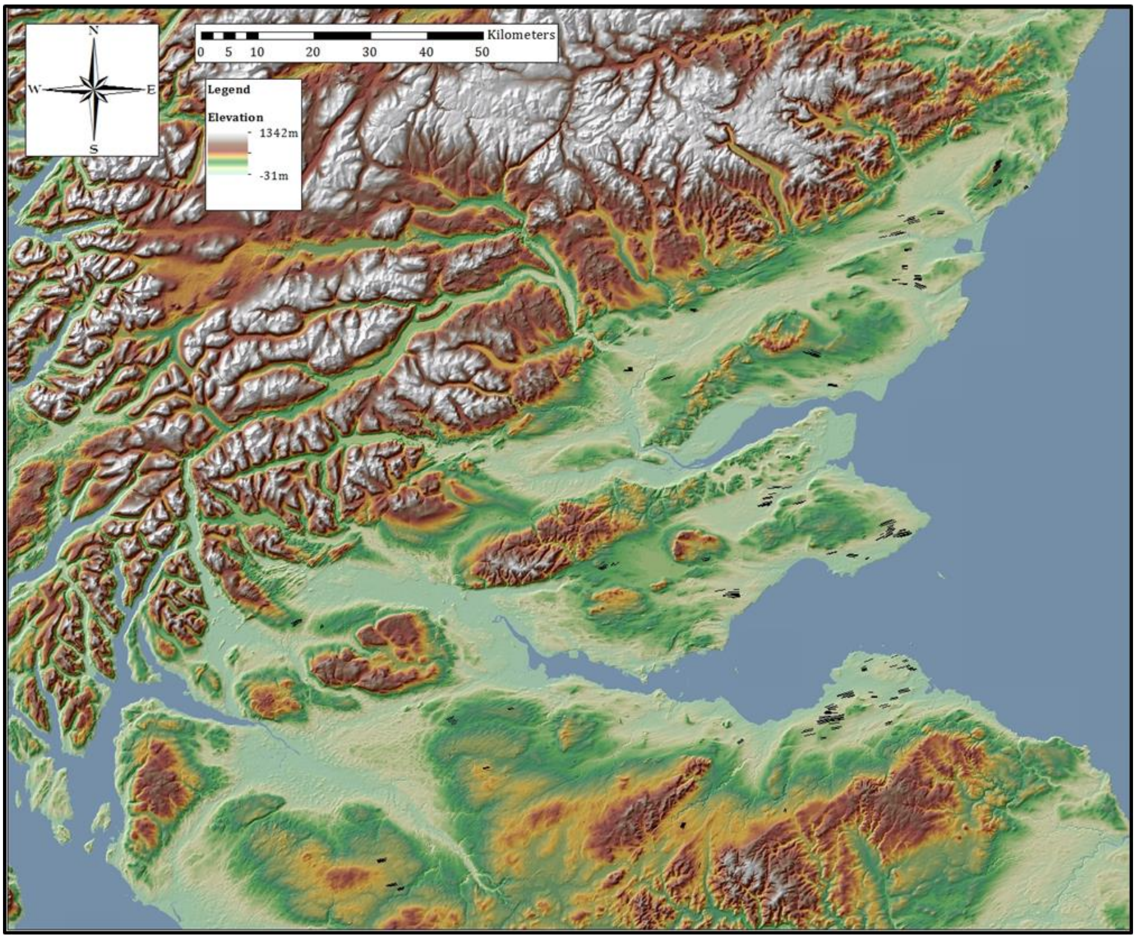

Figure 5.2 - All of the flow traces (black lines) identified in the study area.

5.2.2 Drumlins

Drumlins were identified as a ridge of drift, with no bedrock at the surface, where a break of slope was clearly visible (Figure 5.3). A total of 4,818 were mapped across the study area. Clark *et al.* (2009) studied 58,983 drumlins in Britain and found that drumlins are generally between 250 m and 1,000 m in length, between 120 m and 300 m in width, and have elongation ratios of between 1.7 to 4.1. Clark and Stokes (2005) identified drumlins as a subglacial bedform that can be used in the identification of ice stream activity, particularly in ice stream onset zones (see Literature review 2.2.1). Drumlins are typically associated with ice stream activity where strongly convergent flow-patterns cause elongation ratio increases down flow (Stokes *et al*., 2013).

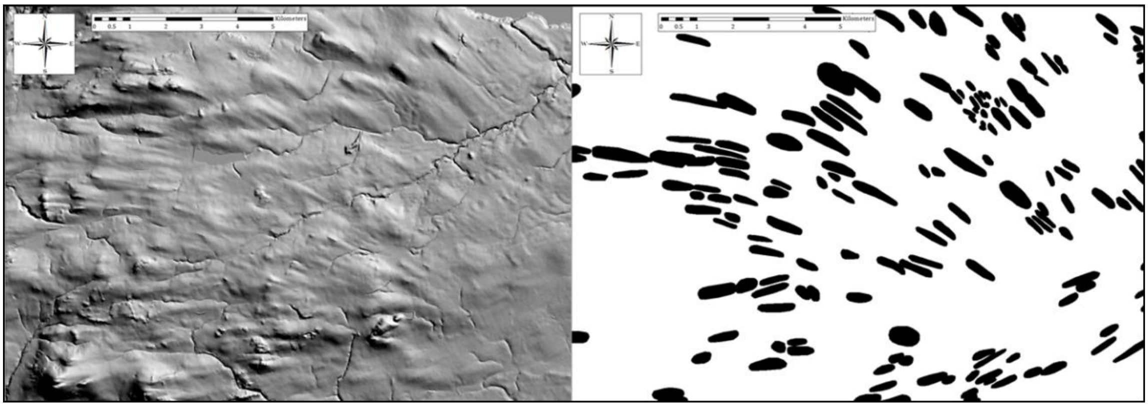

Figure 5.3 - Imagery of the drumlins identified. Drumlins were identified as a ridge of drift, with no bedrock at the surface, where a break of slope was clearly visible. Left image is the NEXTMap DEM used and the right image is the digitised drumlins. Any other types of landforms mapped in this area have been left off this figure. Figure 5.4. shows their distribution throughout the study area.

The drumlins identified in the Firth of Forth area have lengths between 142 m and 4,019 m with a mean of 670 m, widths of between 86 m and 1,129 m with a mean of 260 m, and elongation ratios between 1 and 11 with a mean of 3. The vast majority of drumlins are found on the same geology types as flow traces. 29% are on sandstone with subordinate conglomerate, siltstone and mudstone, and 32% on sedimentary rock cycles (Clackmannan group type 19%, Strathclyde group type 14%). 10% are on mafic lava and mafic tuff. The other geology types either contain no drumlins or very few.

Drumlins are evident across the whole of the lowland regions of the study area. In general, they have an easterly and north easterly orientation. However, in some areas they have a south easterly orientation where they appear to go around highland areas (Figure 5.4).

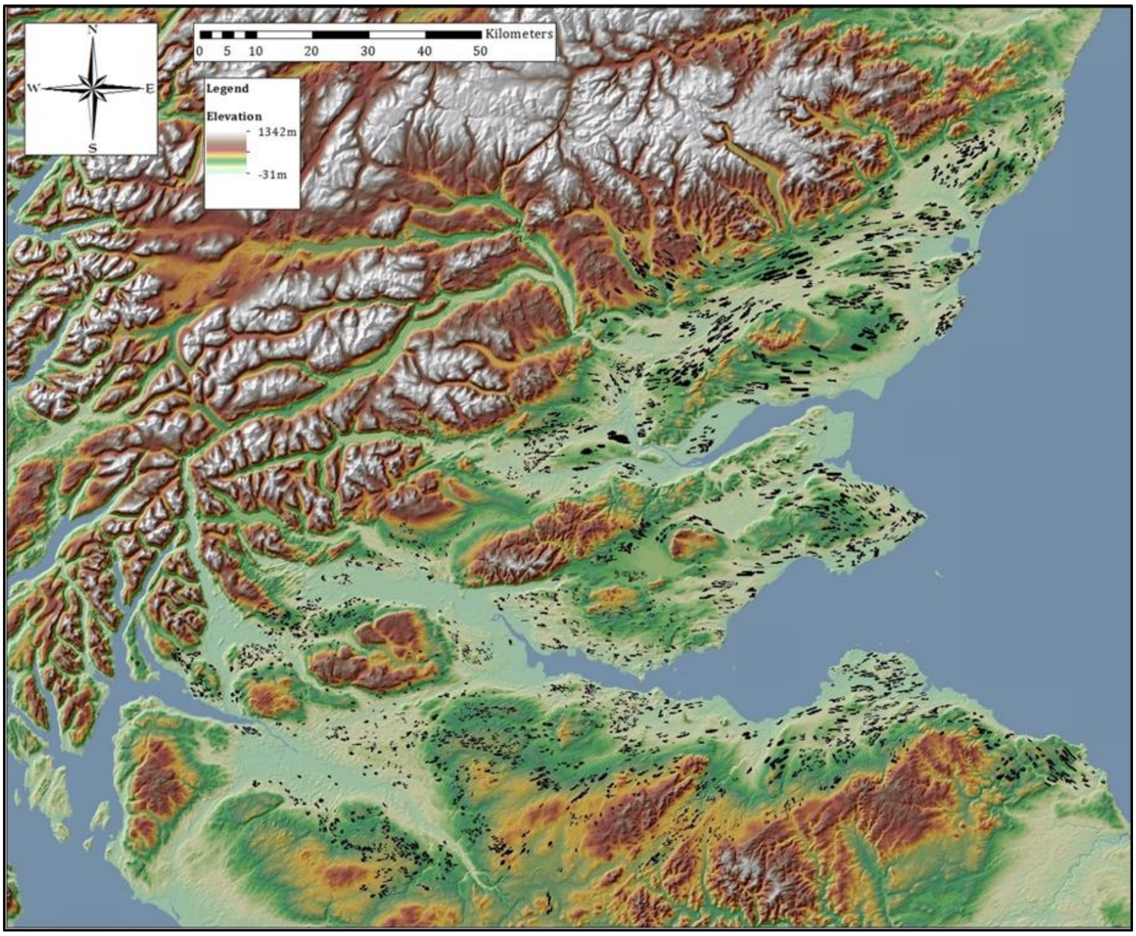

Figure 5.4 - All of the drumlins (black shapes) identified in the study area. The drumlins are black.

5.2.3 Intermediate Forms

Intermediate forms were identified as a ridge of soft sediment with bedrock visible at the surface, and where a break of slope was clearly visible (Figure 5.5). A total of 2,833 were identified in the study area. Hughes (2010) mapped some of these bedforms as drumlins, but there are some differences in morphometry suggesting they are a different bedform and require a separate category. For example, intermediate forms have bedrock clearly visible at the surface and drumlins are ridges of drift with no bedrock clear at the surface.

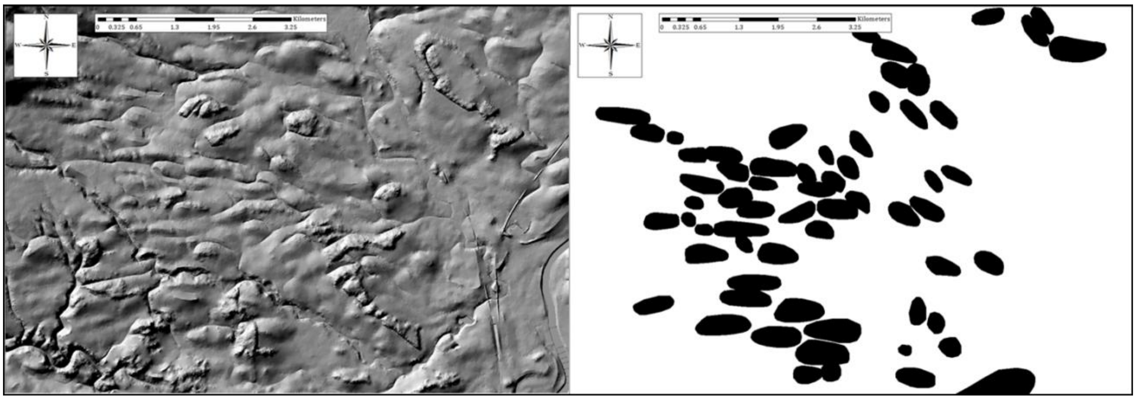

Figure 5.5 - Imagery of the intermediate forms identified. Intermediate forms were identified as a ridge of soft sediment with bedrock visible at the surface, where a break of slope was clearly visible. Left image is the NEXTMap DEM used and the right image is the digitised intermediate forms. Any other types of landforms mapped in this area have been left off this figure. Figure 5.6 shows their distribution throughout the study area.

The intermediate forms identified in the Firth of Forth area have lengths between 151 m 3,385 m with a mean of 566 m. The have widths between 79 m and 908 m with a mean of 266 m. The elongation ratios are between 1 and 6 with a mean of 2. The majority of intermediate forms (29%) are found on the Clackmannan group type sedimentary rock cycles and 23% are found on sandstone with subordinate conglomerate, siltstone and mudstone. 11% are found on mafic lava and mafic tuff.

Intermediate forms are evident across large areas of the lowland regions in the west of the study area. The east coast is more sparsely populated. There are a few intermediate forms found in higher elevated regions (Figure 5.6).

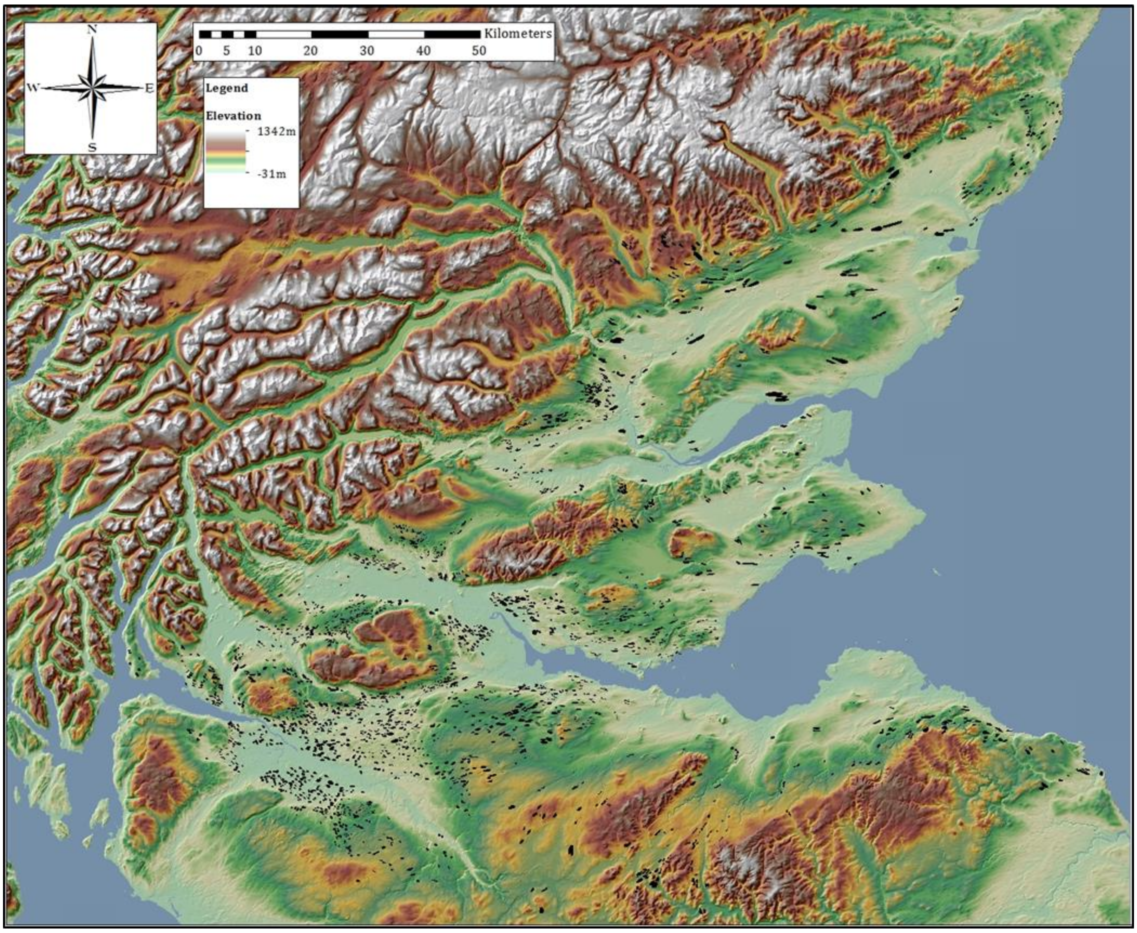

Figure 5.6 - All of the intermediate forms (black shapes) identified in the study area. The intermediate forms are black.

5.2.4 Crag-and-Tails

Crag-and-tails were identified as a bedrock crag with a tail composed of soft sediment (Figure 5.7). A total of 880 were identified across the study area. Hughes (2010) also identified crag-and-tails in the area. These features are a classic and prominent feature of Scotland’s landscape. Benn and Evans (2010) affirm that the bedrock surface around Edinburgh Castle and the Royal mile is a classic example of a crag-and-tail feature, which lies within the study area. Crag-and-tails range in scale from tens of meters to kilometres in length.

The crag-and-tails identified in the Firth of Forth area have lengths between 192 m and 4,352 m with a mean of 333 m, widths between 65 m and 2,576 m, with a mean of 5m, and elongation ratios between 1 and 19, with a mean of 5. The majority of crag-and-tails (26%) are found on mafic lava and mafic tuff. There are relatively large numbers on sandstone with subordinate conglomerate, siltstone and mudstone (19%) and clacknannan group type sedimentary rock cycles (10%).

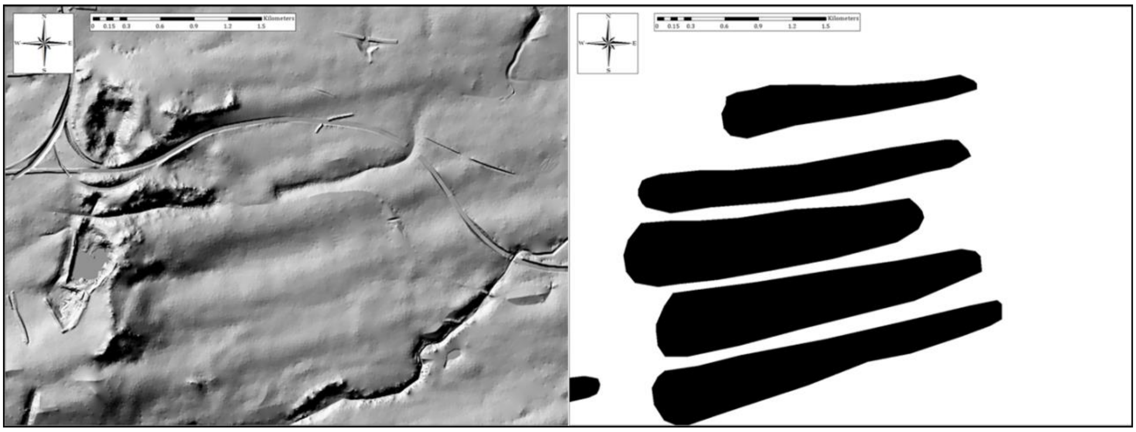

Figure 5.7 - Imagery of the crag-and-tails identified. Crag-and-tails were identified as a bedrock crag with a tail composed of soft sediment. Left image is the NEXTMap DEM used and the right image is the digitised crag-and-tails. Any other types of landforms mapped in this area have been left off this figure. Figure 5.8 shows their distribution throughout the study area.

Crag-and-tails are evident in the eastern section of the study area, but very few were identified in the west. The most densely populated area is in the north east of the study area. In general, they have an easterly and north easterly orientation, but they have a south easterly orientation in some areas. There are clusters in the north east and south east of the study area that demonstrate this south easterly orientation (Figure 5.8).

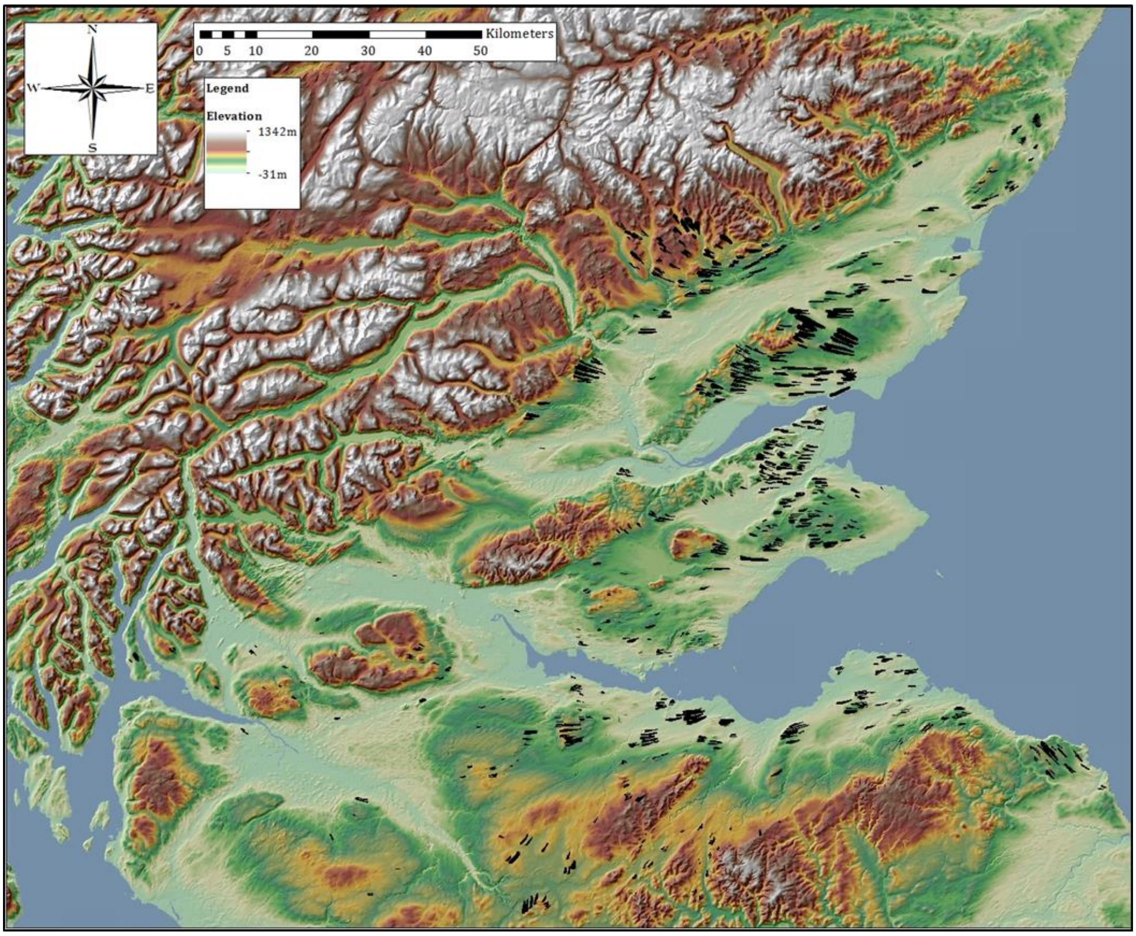

Figure 5.8 - All of the crag-and-tails (black shapes) identified in the study area. The crag-and-tails are black.

5.2.5 Streamlined bedrock ridges

Streamlined bedrock ridges were identified as a low amplitude ridge of streamlined bedrock with no soft sediment visible (Figure 5.9). A total of 1,284 were identified in the study area.

The streamlined bedrock ridges in the study area had lengths between 30 m and 4,320m with a mean of 610 m. The majority of streamlined bedrock ridges are found on sandstone with subordinate conglomerate, siltstone and mudstone. However, there are also high numbers found on psammite and pelite (20%) and mafic lava and mafic tuff (19%). The other geology types contain no or very few streamlined bedrock ridges.

Streamlined bedrock ridges are evident in clusters across the study area. The largest clusters are west of Stirling and north of Edinburgh. They have a general north easterly orientation and are found on the margins of areas with high and low elevation (Figure 5.10; Fig 3.1).

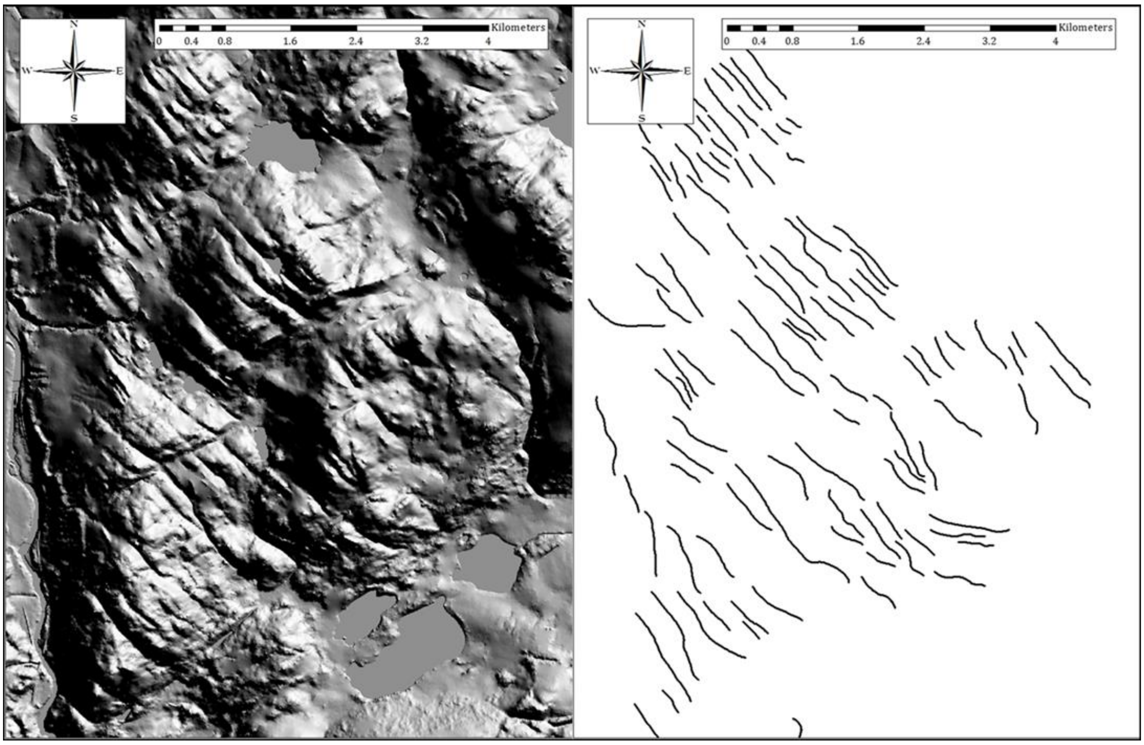

Figure 5.9 - Imagery of the streamlined bedrock ridges identified. Streamlined bedrock ridges were identified as a low amplitude ridge of streamlined bedrock with no soft sediment visible .Left image is the NEXTMap DEM used and the right image is the digitised streamlined bedrock ridges. Any other types of landforms mapped in this area have been left off this figure. Figure 5.10 shows their distribution throughout the study area.

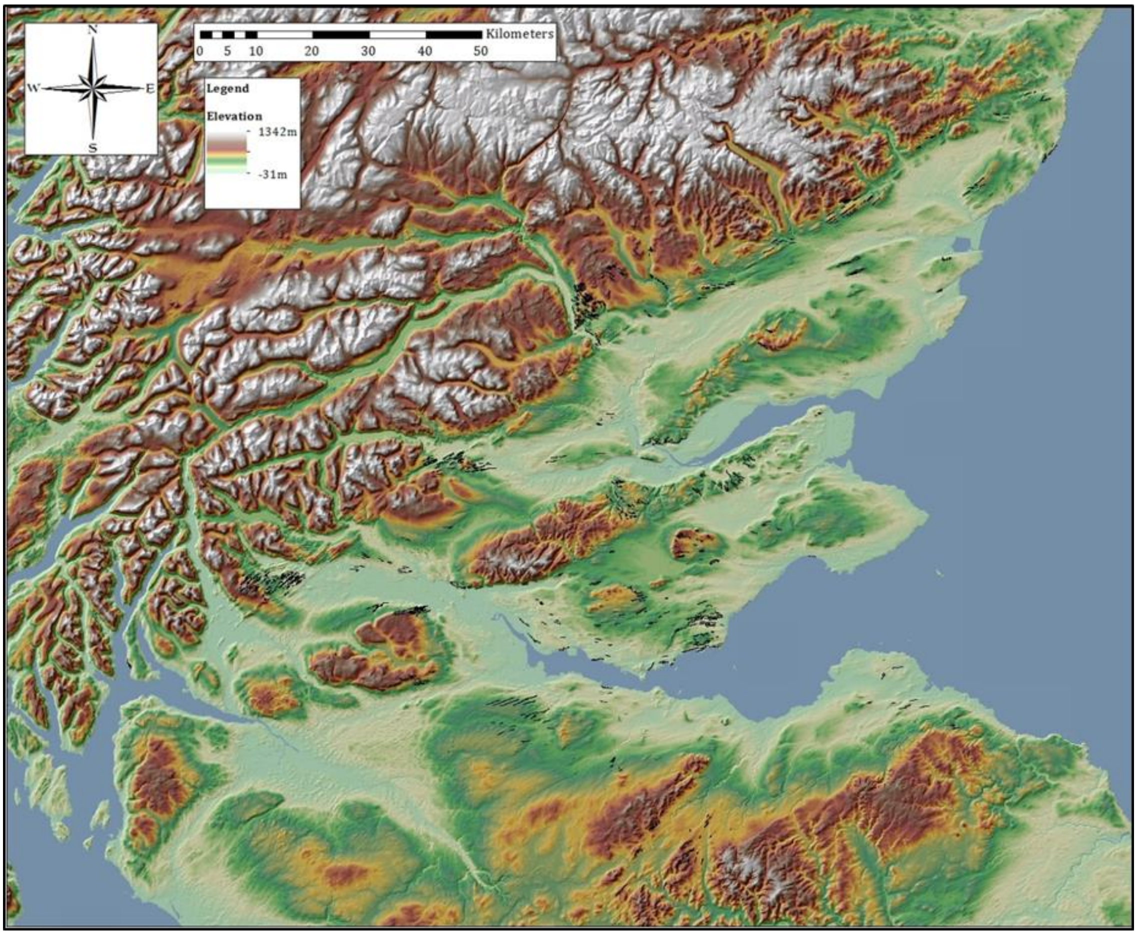

Figure 5.10 - All of the streamlined bedrock ridges (black shapes) identified in the study area. The streamlined bedrock ridges are black.

5.3 Flow-sets and ice margin chronology

Figure 5.11 shows all of the mapped bedforms in the study area, coloured according to their type. In order to analyse the data further, the landforms were grouped into different flow-sets using the criteria set out by Clark (1999), see Methods 4.3.1. A total of 35 separate flow-sets have been identified in the study area (Figure 5.12).

Warm-based deglacial flow-sets are defined as having ice flow traces such as drumlins and flow traces with superimposed, aligned eskers (Stokes *et al*., 2009). The presence of such eskers would suggest that the flow-set formed during or close to deglaciation. No eskers were identified at all in the study area and, therefore, none of the flow-sets fit into this category. Cold-based deglaciation flow-sets only contain a pattern of meltwater features superimposed on old glacial or non-glacial surfaces (Kleman *et al*., 2006). These features would suggest that the flow-set formed during or close to deglaciation on a surface protected by cold-based ice. No meltwater features were identified in the study area and therefore none of the flow-sets identified fit into this category.

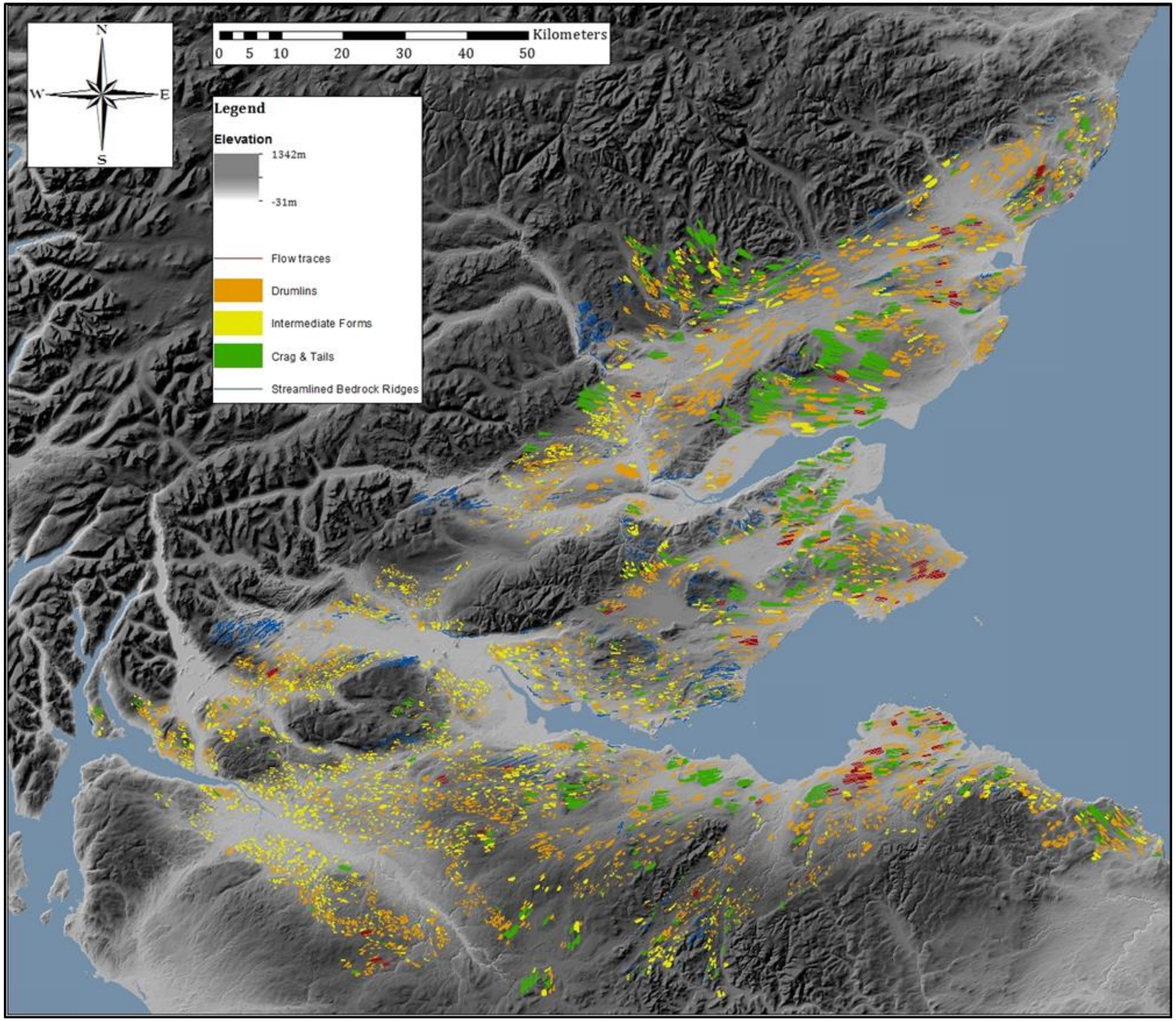

Figure 5.11 - All of the mapped landforms in the study area.

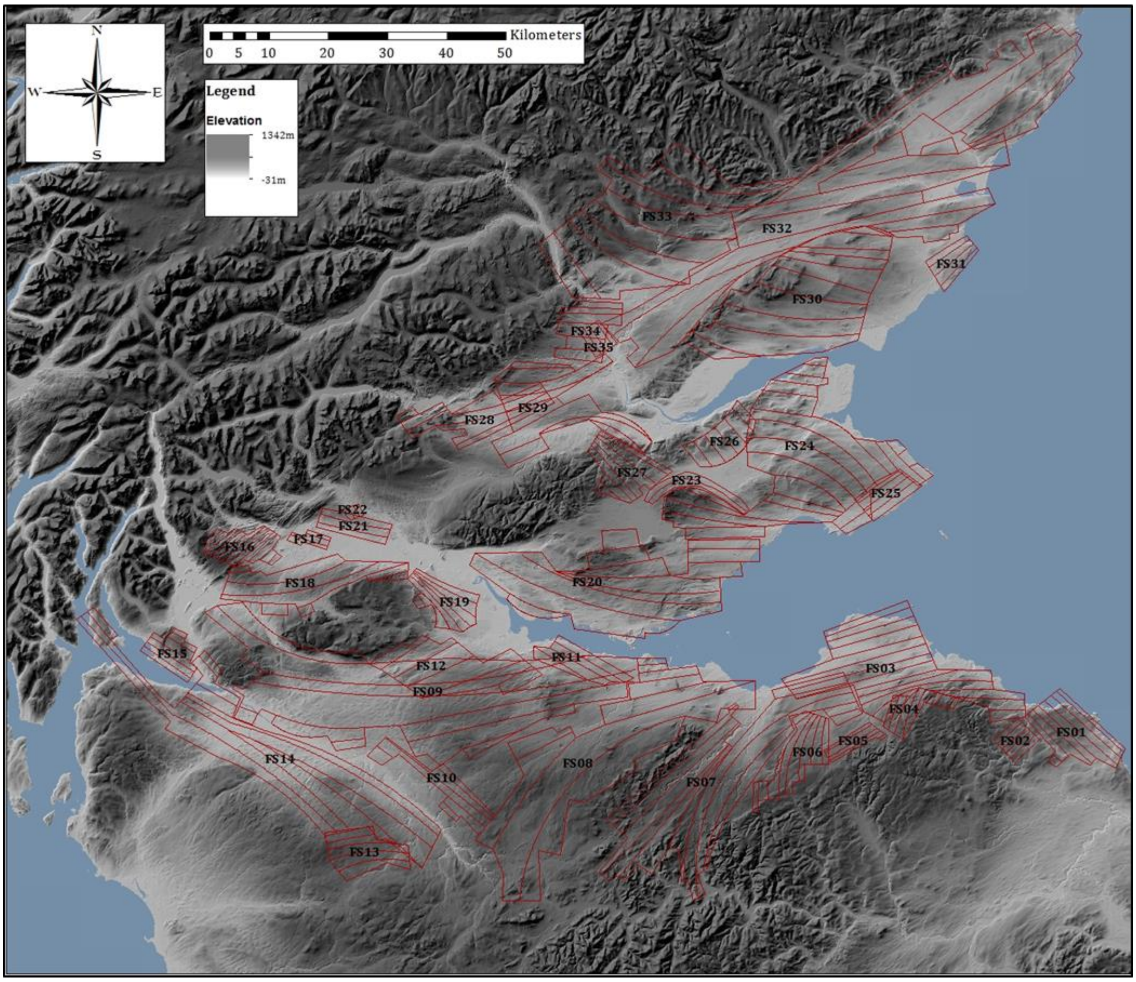

Figure 5.12 - All of the identified flow sets in the study area. 35 separate flow sets have been identified in the study area. Following the Clark (1999) criteria, landforms in a single flow set have a similar orientation and morphometry and are in close proximity.

Event flow-sets contain lots of ice flow traces but lack aligned eskers and moraines (Stokes *et al*., 2009). These features suggest that the flow-set formed prior to deglaciation. Ice stream flow-sets contain mega-scale glacial lineations, convergent ice flow patterns and other criteria indicative of ice stream activity (discussed in Literature review 2.2 and see Table 2.1). These criteria are dependent upon whether the bed is hard, soft or mixed. Such features would suggest that the flow-set formed during ice stream activity. All of the flow-sets identified in this study appear to fit into either the event or ice stream flow-set categories. However, it is difficult to categorise all of the flow-sets because there are a lot of overlapping characteristics and Stokes *et al*. (2009) acknowledged that it can sometimes be difficult to assign a flow-set with high confidence. Complicating this picture, is the possibility that bedrock bedforms may have formed over several ice flow phases or glacial cycles (Roberts *et al*., 2010). As no distinct patterns or distributions of specific bedform types have been identified as part of this mapping exercise, flow-sets are defined on mixed assemblages of both hard and soft bed landforms. The presence of soft bed landforms such as drumlins, therefore, provides some assurance that the flow-sets mapped capture late-phase or the final phase of ice flow in a specific area.

In total, seven flow-sets have been identified as event flow-sets (FS11, FS12, FS13, FS16, FS17, FS22 and FS24). All of the others have been classified as ice stream flow-sets (Table 5.1) based on their shape and the elongation of the bedforms that they contain. Ice stream activity appears to be dominated by five large flow-sets, two in the north and three in the south. The two large northern flow-sets run through Strathtay and Strathmore (FS32 and FS33). The flow-sets are made up of all five landforms and they have a north easterly orientation (Table 5.1). The three large southern flow-sets run through Strathblane, Strathgryfe and Clydesdale around the Pentland Hills (FS8, FS9, FS14). FS8 is made up of drumlins, intermediate forms, crag-and-tails and streamlined bedrock ridges and has a general north easterly orientation. FS9 is made up of all five landforms and has a general easterly orientation. FS14 is made up of drumlins, intermediate forms, crag-and-tails and streamlined bedrock ridges and has a general easterly orientation. These dominant flow-sets are joined by other, smaller flow-sets representing ice flowing down from the highlands. These flow-sets exhibit some of the characteristics of fast flow ice streaming, such as sharply delineated margins and elongate bedforms (Table 5.1).

There are also coherent convergent patterns in numerous flow-sets. The two large northern flow-sets converge through Strathblane to Stonehaven. FS7 and FS8 run around the east and west of the Pentland Hills before converging and flow continues around the Lammermuir Hills to the North Sea. There is also evidence of some flow-sets cross-cutting others. North of Perth, where Strathtay meets Strathmore, FS34 and FS35 crosscut. FS34 is flowing in an easterly direction and converges with the larger flow-sets running through Strathmore whereas FS35 is flowing in a south-easterly direction towards Perth. This cross-cutting can also be seen on a larger scale in the lowland area around Campsie Fells. FS9, FS11 and FS12 flow in easterly, south-easterly and north-easterly directions respectively. FS9 and FS11 then converge with FS8 around the north of the Pentland Hills.

Table 5.1 summarises the key data for each flow-set. The flow-set with the largest number of landforms is FS9 which runs through Strathblane and around Campsie Fells. It has an easterly orientation. The flow-sets with smallest number of landforms are FS2 and FS5 which are located around the Lammermuir Hills and FS22 which is located close to the highland boundary fault, near Strallallan. All of these small flow-sets are on a boundary between high and low elevation.

Table 5.1 - Characteristics of each flow set detailing size, direction of flow and landforms identified. It also shows which margin positions each flow set was active in and what each flow set has been classified as.

Flow set	Characteristics	Chronological information	Classification
1	Small flow set flowing south easterly. It contains elongate bedforms. It contains drumlins, intermediate forms and crag-and-tails.	It is switched on at margin positions 1 and 2.	Ice stream
2	Small flow set flowing north easterly. It contains drumlins.	It is switched on at margin position 1.	Ice stream
3	Medium flow set flowing easterly. It contains elongate bedforms. It contains flow traces, drumlins, intermediate forms, crag and tails and streamlined bedrock ridges.	It is switched on at margin positions 1 and 2.	Ice stream
4	Small flow set flowing north. It contains drumlins, intermediate forms and crag-and-tails.	It is switched on at margin position 1.	Ice stream
5	Small flow set flowing easterly. It contains drumlins and intermediate forms.	It is switched on at margin position 1.	Ice stream
6	Medium flow set flowing north. It contains flow traces, drumlins, intermediate forms and crag-and-tails.	It is switched on at margin position 1.	Ice stream
7	Large flow set flowing north easterly. It has a convergent onset zone. It contains flow traces, drumlins, intermediate forms, crag-and-tails and streamlined bedrock ridges.	It is switched on at margin positions 1, 2 and 3.	Ice stream
8	Large flow set flowing north easterly. It has a convergent onset zone and abrupt lateral margins. It contains flow traces, drumlins, intermediate forms, crag-and-tails and streamlined bedrock ridges.	It is switched on at margin positions 1, 2 and 3.	Ice stream
9	Large flow set flowing easterly. It has a convergent onset zone. It contains elongate bedforms. It contains flow traces, drumlins, intermediate forms, crag-and-tails and streamlined bedrock ridges.	It is switched on at margin positions 1, 2, 3 and 4.	Ice stream
10	Small flow set flowing south easterly. It contains drumlins, intermediate forms and crag-and-tails.	It is switched on at margin position 4.	Ice stream
11	Small flow set flowing south easterly. It contains flow drumlins, intermediate forms, crag-and-tails and streamlined bedrock ridges.	It does not clearly fit into any margin positions.	Event
12	Medium flow set flowing north easterly. It contains flow traces, drumlins, intermediate forms, crag-and-tails and streamlined bedrock ridges.	It does not clearly fit into any margin positions.	Event
13	Small flow set flowing easterly. It contains flow traces, drumlins, intermediate forms and crag-and-tails.	It does not clearly fit into any margin positions.	Event
14	Large flow set flowing south easterly. It has abrupt lateral margins. It contains elongate bedforms. It contains drumlins, intermediate forms, crag-and-tails and streamlined bedrock ridges.	It is switched on at margin position 4.	Ice stream
15	Small flow set flowing south easterly. It contains drumlins, intermediate forms and	It is switched on at margin positions 1, 2,	Ice stream

	crag-and-tails.	3 and 4.	
16	Small flow set flowing north easterly. It contains drumlins, intermediate forms, and streamlined bedrock ridges.	It does not clearly fit into any margin positions.	Event
17	Small flow set flowing easterly. It contains drumlins and intermediate forms.	It does not clearly fit into any margin positions.	Event
18	Medium flow set flowing north easterly. It has abrupt lateral margins. It contains elongate bedforms. It contains flow traces, drumlins, intermediate forms, crag-and-tails and streamlined bedrock ridges.	It is switched on at margin positions 3 and 4.	Ice stream
19	Small flow set flowing south easterly. It has abrupt lateral margins. It contains drumlins and intermediate forms.	It is switched on at margin positions 3 and 4.	Ice stream
20	Large flow set flowing easterly. It contains elongate bedforms. It contains flow traces, drumlins, intermediate forms, crag-and-tails and streamlined bedrock ridges.	It is switched on at margin positions 1, 2 and 3.	Ice stream
21	Small flow set flowing easterly. It contains drumlins, intermediate forms, crag-and-tails and streamlined bedrock ridges.	It is switched on at margin positions 1, 2 and 3.	Ice stream
22	Small flow set flowing south easterly. It contains drumlins and intermediate forms.	It does not clearly fit into any margin positions.	Event
23	Small flow set flowing easterly. It has abrupt lateral margins. It contains drumlins and intermediate forms.	It is switched on at margin positions 2 and 3.	Ice stream
24	Large flow set flowing easterly. It contains flow traces, drumlins, intermediate forms, crag-and-tails and streamlined bedrock ridges.	It does not clearly fit into any margin positions.	Event
25	Small flow set flowing north easterly. It contains flow traces and drumlins.	It does not clearly fit into any margin positions.	Ice stream
26	Small flow set flowing south easterly. It contains drumlins, intermediate forms, crag-and-tails and streamlined bedrock ridges.	It is switched on at margin position 1.	Ice stream
27	Small flow set flowing south easterly. It contains drumlins, intermediate forms, crag-and-tails and streamlined bedrock ridges.	It is switched on at margin position 1.	Ice stream
28	Medium flow set flowing north easterly. It contains drumlins, intermediate forms and streamlined bedrock ridges.	It is switched on at margin positions 2 and 3.	Ice stream
29	Medium flow set flowing north easterly. It contains drumlins, intermediate forms, crag-and-tails and streamlined bedrock ridges.	It is switched on at margin positions 2 and 3.	Ice stream
30	Medium flow set flowing easterly. It contains elongate bedforms. It contains flow traces, drumlins, intermediate forms, crag-and-tails and streamlined bedrock ridges.	It does not clearly fit into any margin positions.	Ice stream
31	Small flow set flowing north easterly. It contains drumlins and intermediate forms.	It is switched on at margin positions 1 and 2.	Ice stream
32	Large flow set flowing north easterly. It has abrupt lateral margins. It contains elongate bedforms. It contains flow traces, drumlins, intermediate forms, crag-and-tails and streamlined bedrock ridges.	It does not clearly fit into any margin positions.	Ice stream
33	Large flow set flowing north easterly. It contains flow traces, drumlins, intermediate	It does not clearly fit into any margin	Ice stream

	forms, crag-and-tails and streamlined bedrock ridges.	positions.	
34	Small flow set flowing easterly. It contains flow traces, drumlins, intermediate forms and crag-and-tails.	It is switched on at margin positions 2 and 3.	Ice stream
35	Small flow set flowing south easterly. It contains drumlins and intermediate forms.	It does not clearly fit into any margin positions.	Ice stream

Section 5.4 Summary

To summarise, five different types of landform were mapped; flow traces, drumlins, intermediate forms, crag-and-tails and streamlined bedrock ridges. 256 flow traces were mapped. They were generally found in clusters with an easterly or north easterly orientation. 4,818 drumlins were mapped. They were found across the whole study area generally with an easterly or north easterly orientation. 2,833 intermediate forms were mapped. They were found across the whole study area. 880 crag-and-tails were mapped. They were mostly found in clusters in the east of the study area. 1,284 streamlined bedrock ridges were mapped. They were generally found in clusters at the margins of high and low elevation. It is important to note that there is a continuum of landforms types and it was not always easy to differentiate between them. Therefore, there may be some dispute over the classification of some landforms. Finally, 35 flow sets were identified; 28 were classified as ice stream flow sets and seven were classified as event flow sets due to the landforms contained within them and the patterns they exhibited. However, it is important to note, again, that the classification of flow-sets is also difficult do to numerous overlapping characteristics.

Chapter 6 – Discussion

6.1 Introduction

The overall aim of this project was to determine if the Firth of Forth area contains glacial geomorphological evidence of palaeo-ice stream activity. The specific objectives were to:

- Examine and characterise the glacial geomorphology of the Forth region using remote sensing
- To use established criteria, from both soft-bedded and hard-bedded ice streams (e.g. Stokes and Clark, 1999; Krabbendam *et al.,* 2016), to test whether the Firth of Forth was the location of an ice stream
- To examine the subglacial landsystem and determine the relative roles of bedrock geology and topography
- To reconstruct the general chronology and glacial history of the area
- To understand ice stream influence on regional ice sheet history

This chapter will discuss each of these objectives in turn. Section 6.2 is concerned with the chronology and glacial history of ice stream activity and looks at the influence of these findings on regional ice sheet history. Section 6.3 documents the use of geomorphological evidence to reconstruct ice stream activity in the Firth of Forth area. Section 6.4 discusses the implications for geological control on bedform morphometry and type.

6.2 Reconstruction of glacial history and ice stream flow-sets

The orientation of the bedforms suggest that the ice stream splits into two at some point and the flow-sets show two distinct flow patterns. Ongoing research of the Forth offshore print has revealed that the ice stream does indeed split into two trunks off shore which fits with the two distinct flow directions identified onshore. Therefore, the study area has been analysed as a whole and as two separate sections, north and south.

Some flow-sets are very clearly topographically constrained whereas others are not. It is assumed that during the initial stages of a glacial period the ice flow is topographically constrained. As the ice thickens, it may ignore topography. During deglacial periods, the ice thins again and becomes topographically constrained again. It is therefore assumed that the flow-sets that appear to ignore topography (e.g. FS30, FS27, FS26) are older and were active during the Last Glacial Maximum. However, some of the flow-sets that are constrained by topography will have been active during different periods of deglaciation.

Figure 6.1a show the northern flow-sets that are not controlled by topography. They are oriented in a south easterly direction. Figure 6.1b shows the northern flow-sets that are constrained by topography. The flow-sets are oriented in a north easterly direction and flow through and around areas of high elevation. Figure 6.1c show the flow-sets in the south east. Some of these flow-sets are very clearly topographically constrained and some flow down from high elevation. They flow around high elevation in a north easterly then south easterly direction. Figure 6.1d shows the south west flow-sets which are again topographically constrained and flowing in an easterly direction. It is therefore clear that bedforms mapped in the Forth area represent different flow phases.

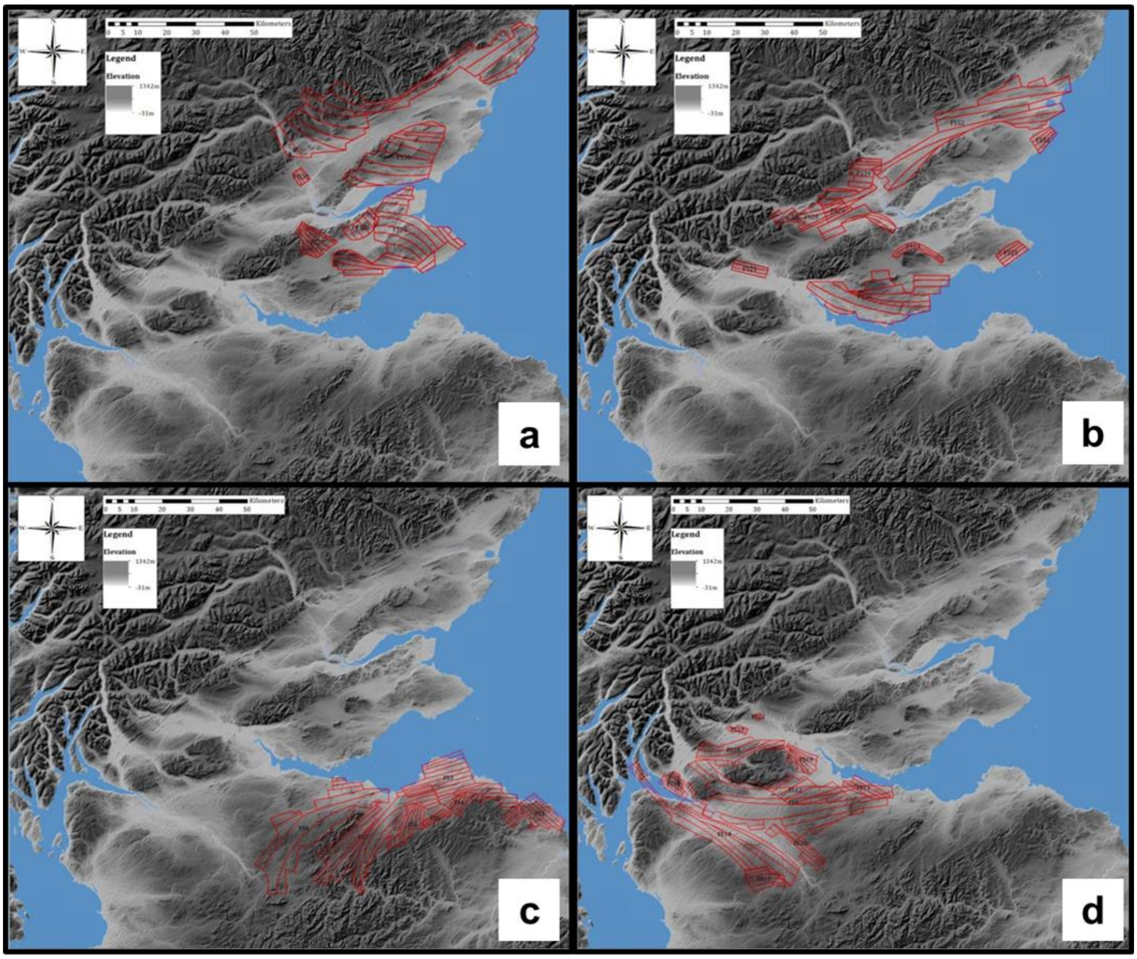

Figure 6.1- a) This shows the northern flow sets that are not controlled by topography. They are oriented in a south easterly direction. b) This shows the northern flow sets that are constrained by topography. c) This shows the south east flow sets. Some of these flow sets are very clearly topographically constrained and some flow down from high elevation. They flow around high elevation in a north easterly then south easterly direction. d) This shows the south west flow sets which are again topographically constrained and flowing in an easterly direction.

The southern section of the ice stream appears to be almost completely topographically constrained with the exception of four small flow-sets flowing from high to low elevation. The northern section of the ice stream is, however, more difficult to reconstruct, as some flow-sets are topographically controlled and some are not. Without determining the age of the bedforms, it is difficult to know when the flow-sets were active. The existence of two separate drumlin fields offshore that show ice flowing north to south has been identified, but their age is also unknown (pers. comm. Dave Roberts and Heather Stewart).

The uncertainty about the northern section of the ice stream has led to the presentation of two different scenarios. Scenario one is that the whole ice stream is topographically controlled in some part and splits at maximum extent creating two trunks that are active throughout (Fig 6.2a). Scenario two is that, during maximum glaciation, the northern section of the ice stream is not controlled by topography at all and flows in a south easterly direction where it joins with the southern section of the ice stream flowing into the south trunk (Fig 6.2b). Then, during deglaciation and when the ice thins, the north section becomes topographically constrained and is forced to flow in a north easterly direction splitting the ice stream and forming the second (northern) trunk. Both scenarios include the creation of two separate trunks. The only difference is the time at which each trunk is created. The offshore print could be linked to the flow phases we see onshore but it is difficult to be certain.

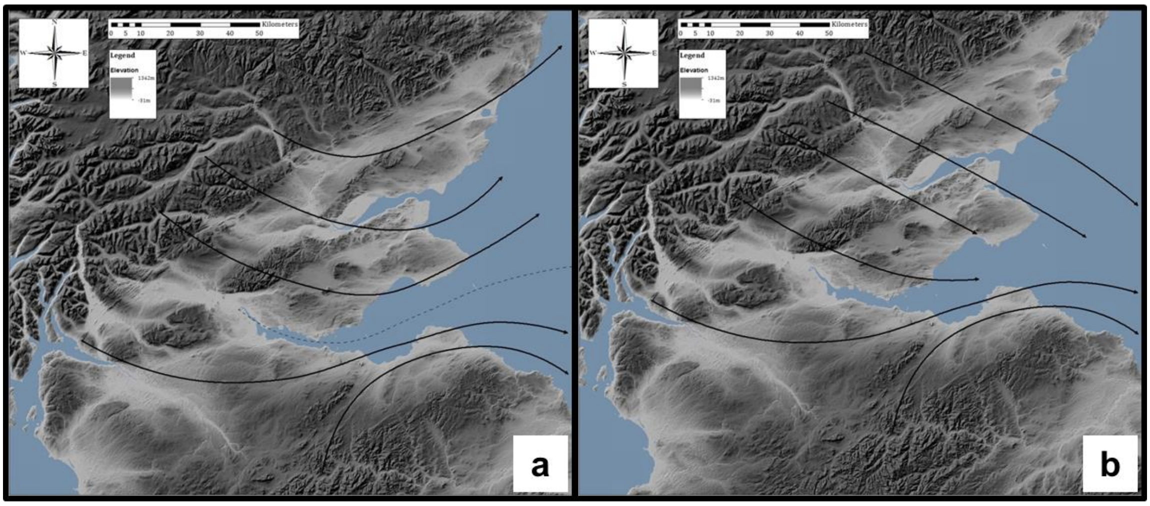

Figure 6.2 - a) Scenario one. The whole ice stream is topographically controlled in some part and splits at maximum extent creating two trunks that are active throughout. b) Scenario two. During maximum glaciation, the northern section of the ice stream is not controlled by topography at all and flows in a south easterly direction where it joins with the southern section of the ice stream flowing into the south trunk.

Clark *et al*. (2012) derived a pattern of retreat for the whole British-Irish Ice Sheet using remote sensing and incorporating previously published evidence. Fig 6.3 shows their reconstruction based on their analysis of meltwater channels, eskers, ice-dammed lakes and drumlins. When producing the timing constraints for the pattern of retreat on the east coast of England and the North Sea (including the study area),

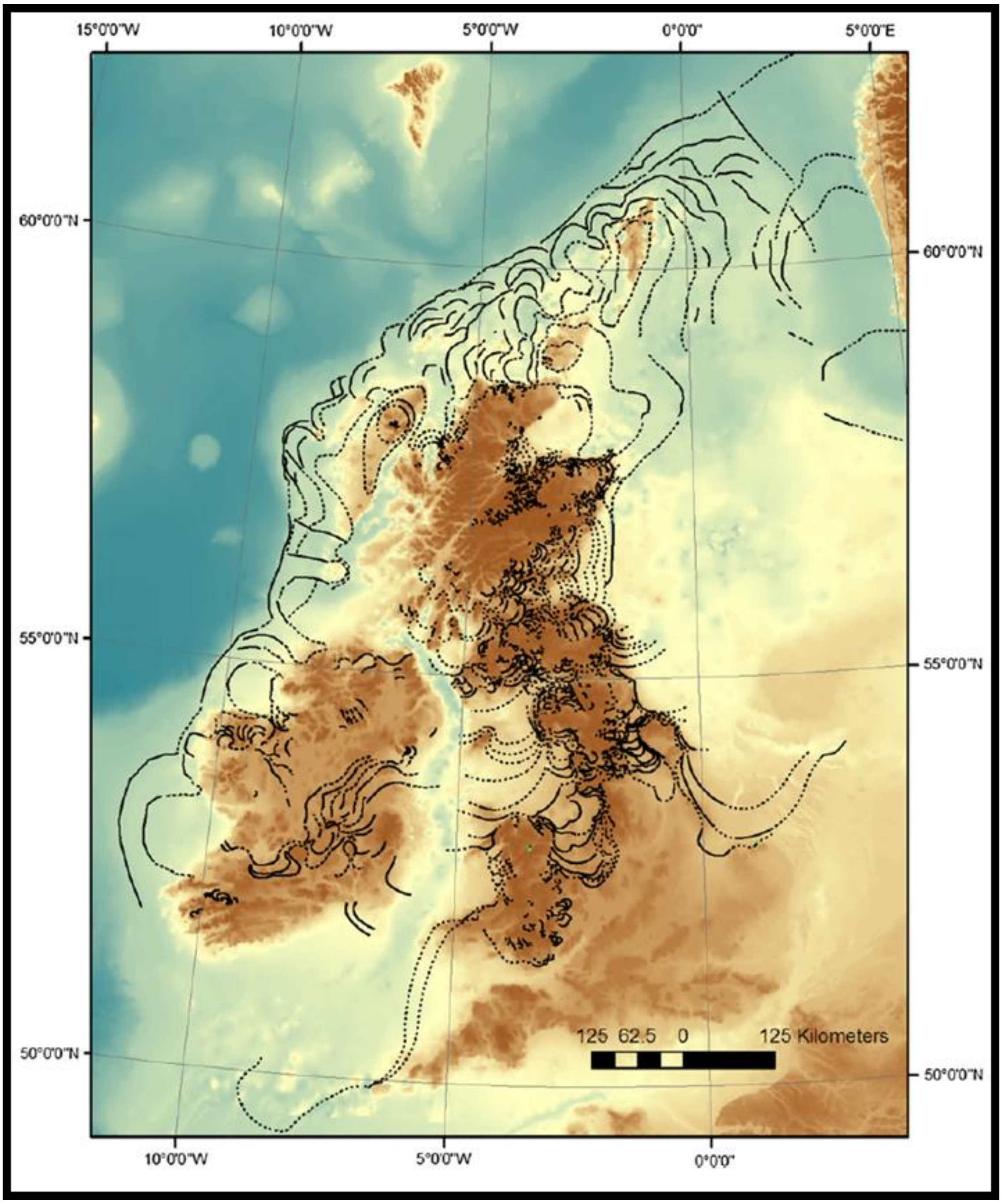

Figure 6.3 - This shows the (Clark et al., 2012) reconstruction based on their analysis of meltwater channels, eskers, ice-dammed lakes and drumlins Clark et al (2012).

Clark *et al*. (2012) faced difficulties due to a lack of evidence. They therefore presented two scenarios (Fig 6.4) which differ with regard to the deglaciation of the North Sea, including the Firth of Forth region, further offshore. It is therefore difficult to create accurate margin positions for the study area.

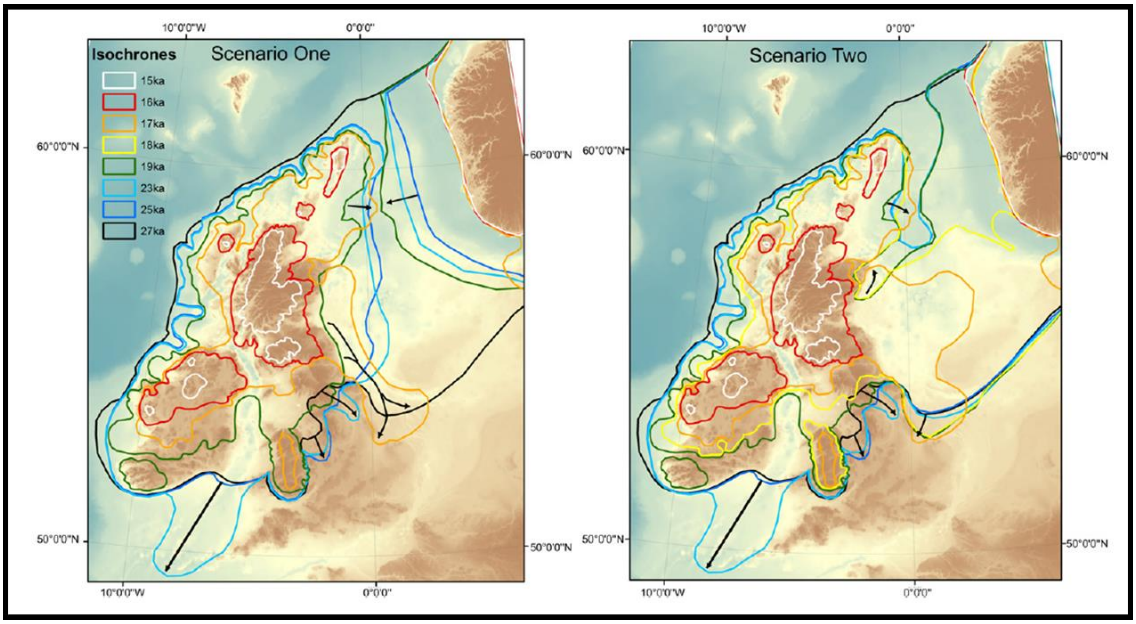

Figure 6.4 - When producing the timing constraints for the pattern of retreat on the east coast of England and the North Sea (including the study area), Clark et al (2012) faced difficulties due to a lack of evidence. They therefore presented two scenarios which differ with regard to the deglaciation of the North Sea (Clark et al., 2012).

Four new margin positions for the Forth area have been reconstructed using the location and orientation of the flow-sets identified in this study (see section 4.3.2 for detailed information on how this was done). Fig 6.5 shows the four margin positions. The dates of these new margin positions were approximated and inferred using the confirmed margin positions in Clark *et al.* (2012). Figures 6.6a, 6.6b, 6.6c and 6.6d show the ice cover, in the study area, at each position. Some areas north and south of the study area will also have been covered in ice however this is omitted from these figures for clarity (see figures 6.3 and 6.4 for full ice cover and extent across the whole of the BIIS).

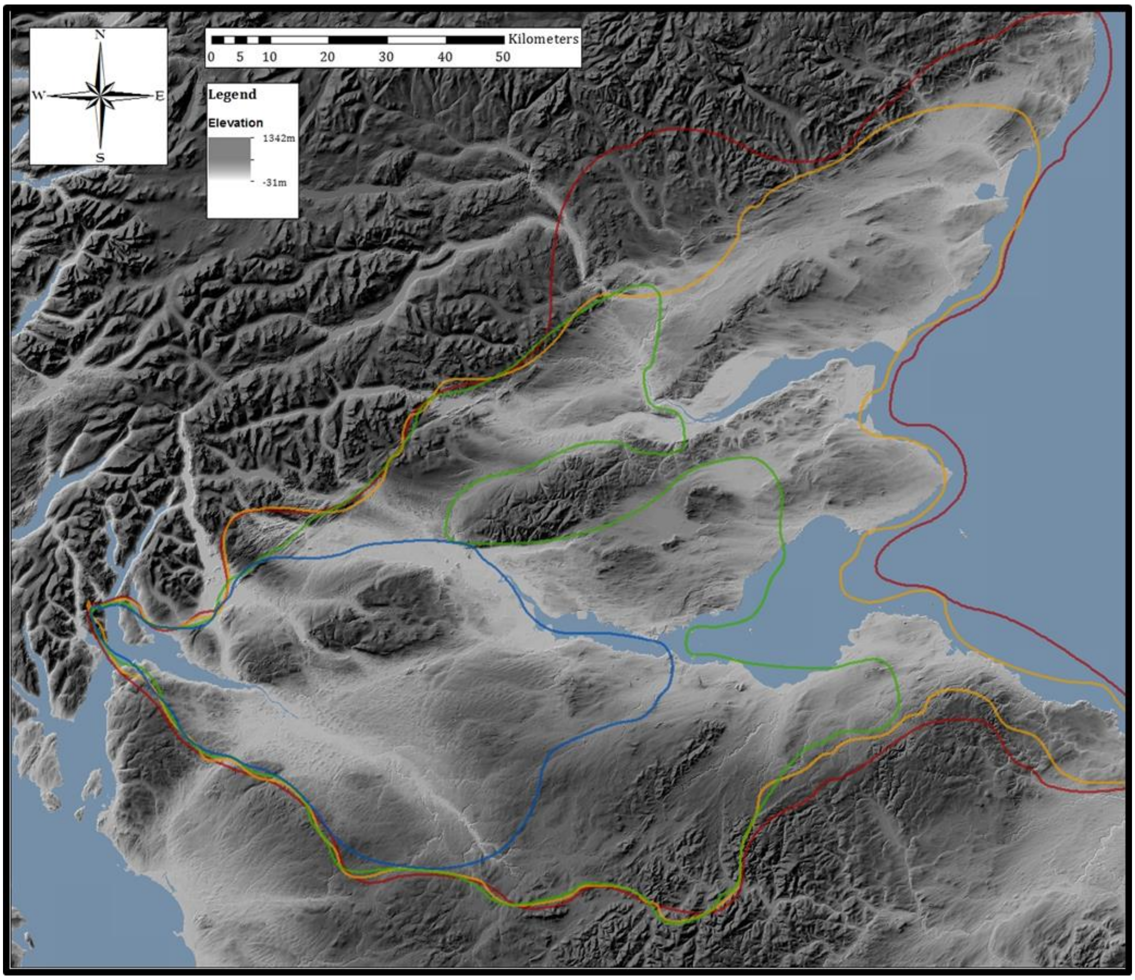

Figure 6.5 - This shows the four new hypothesised margin positions. They were reconstructed using the location and orientation of the flow-sets identified in this study.

Figure 6.6a shows ice cover in the study area at margin position 1. The ice covers the whole of the study area and reaches the onshore/offshore divide. This margin position links well with one of the positions in Clark *et al*. (2012) (Figure 6.4) and is assumed to represent ice cover at around 19 ka when the ice had retreated from off shore and was now predominantly onshore (Clark *et al*. (2012) (Figure 6.4). Figure 6.6b shows ice cover in the study area at margin position 2. The ice has retreated slightly and is now more controlled by topography. This margin position lies in between the Clark *et al.* (2012) margin positions dated at 19 ka and 16 ka. By margin position 3 (Figure 6.6c), the northern section of the ice stream has retreated more than the south. The high elevation patches that were covered by ice are now ice free and the ice is completely topographically constrained. This margin position corresponds in location to a position by Clark *et al.* (2012) dated at 16 ka. By margin position 4 (Figure 6.6d), the ice stream has retreated to consist of only the south west section of the ice which again is topographically constrained. Some of the higher areas may also have been ice free during the later stages of deglaciation. This margin position lies between two positions from Clark *et al.* (2012) dated at 16 ka and 15

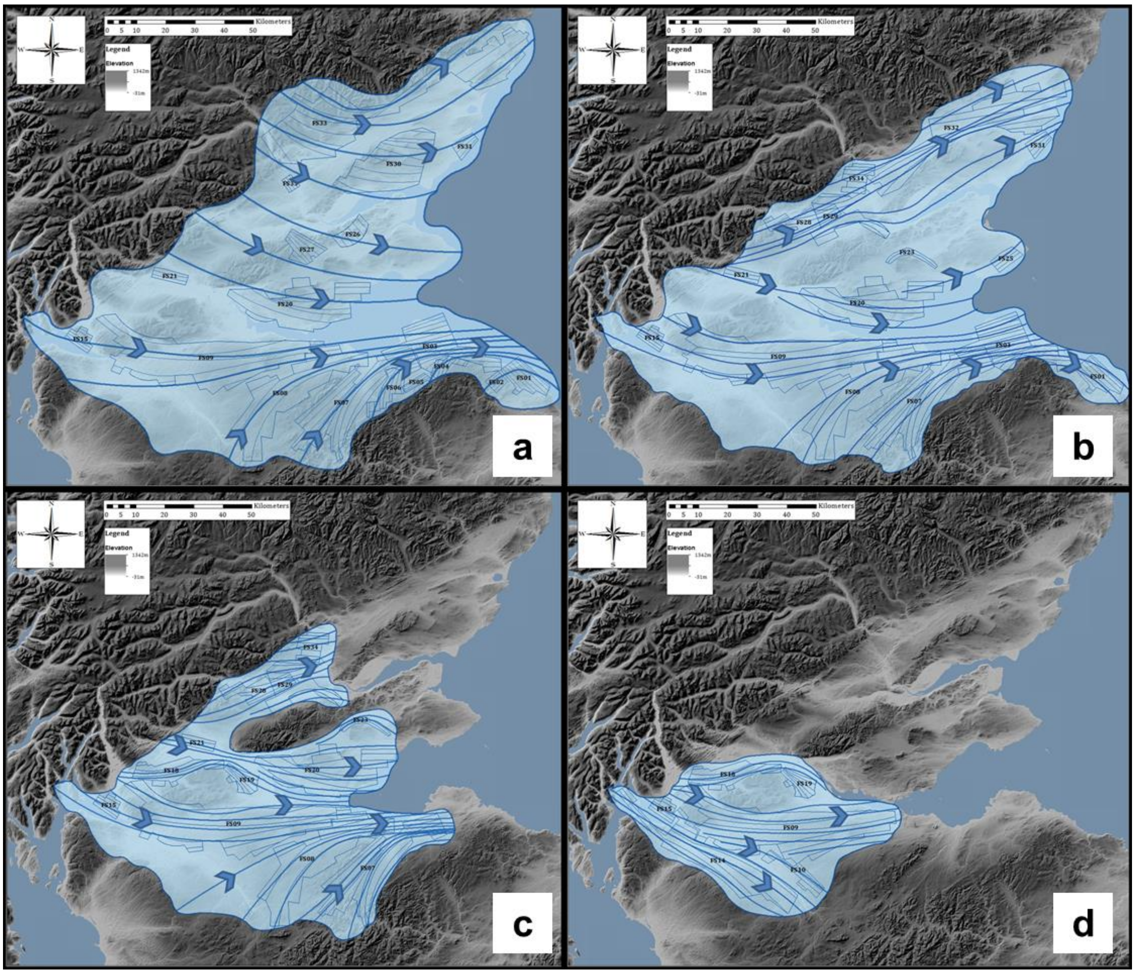

Figure 6.6 - a)This shows ice cover in the study area at margin position 1. The ice covers the whole of the study area and reaches the onshore/offshore divide. This margin position links well with one of the positions in Clark et al. (2012)(Figure 6.4) and is assumed to represent ice cover at around 19 ka when the ice had retreated from off shore and was now predominantly onshore (Clark et al. (2012)(Figure 6.4). b)This shows ice cover at margin position 2. The ice has retreated slightly and is now more controlled by topography. The ice has retreated slightly and is now more controlled by topography. This margin position lies in between the Clark *et al.* (2012) margin positions dated at 19 ka and 16 ka. c) This shows margin position 4. The ice stream has retreated to consist of only the south west section of the ice which again is topographically constrained. d) This shows margin position 4. The ice stream has retreated to consist of only the south west section of the ice which again is topographically constrained.

This paper is the first to present evidence and formally identify the Forth area as a palaeo-ice stream. It is also clear that this is the largest terrestrial onshore imprint of a palaeo-ice stream identified on the east coast of the BIIS.

The remote sensing work undertaken in this study has allowed for an initial reconstruction of the glacial history of the area. However, there is a need for further research to create a more accurate reconstruction. For example, the influence of bedrock type and structure on bedform evolution needs to be thoroughly appraised. Detailed chronological data is also required to constrain and test the age of the reconstructed margin positions. Improved numerical modelling of the ice steam will also enable future researchers to assess the key variables that control ice stream dynamics and to explore the dynamic behaviour of the ice stream through time.

6.3 Evidence for ice stream activity

As noted, the main aim of this project was to determine if the Firth of Forth area represents a palaeo-ice stream, as has been hypothesised by Golledge and Stoker (2006), Bradwell *et al.* (2008) and Hubbard *et al*. (2009). This section will examine the characteristics of the glacial geomorphological imprint (objective 1). The distribution of the features identified suggest that both soft and hard bed landforms are juxtaposed across the study area with no specific up-ice/down-ice changes in their pattern/distribution. However, it should be noted that they were developed primarily with a soft-bedded ice stream in mind, and not all of the criteria will apply to a hard- or mixed-bed ice stream imprint. As the Forth area has a mixed bed, additional criteria relating to theories on bedrock forms in ice stream locations (Roberts and Long, 2005; Eyles, 2012; Krabbendam *et al*.,

2016) will also be analysed to explore whether it is possible to see a signature of fast ice flow on hard bedded ice streams. Each of the criteria will now be looked at in turn and the geomorphological signature identified in the Firth of Forth will be analysed.

6.3.1 Characteristic shape and dimensions

The characteristic shape of a contemporary ice stream is described as an onset zone of converging flow lines feeding in to a trunk of streaming ice (Stokes and Clark, 1999). The overall shape of the Forth imprint is one of divergence. Flow is visible north easterly, easterly and south easterly.

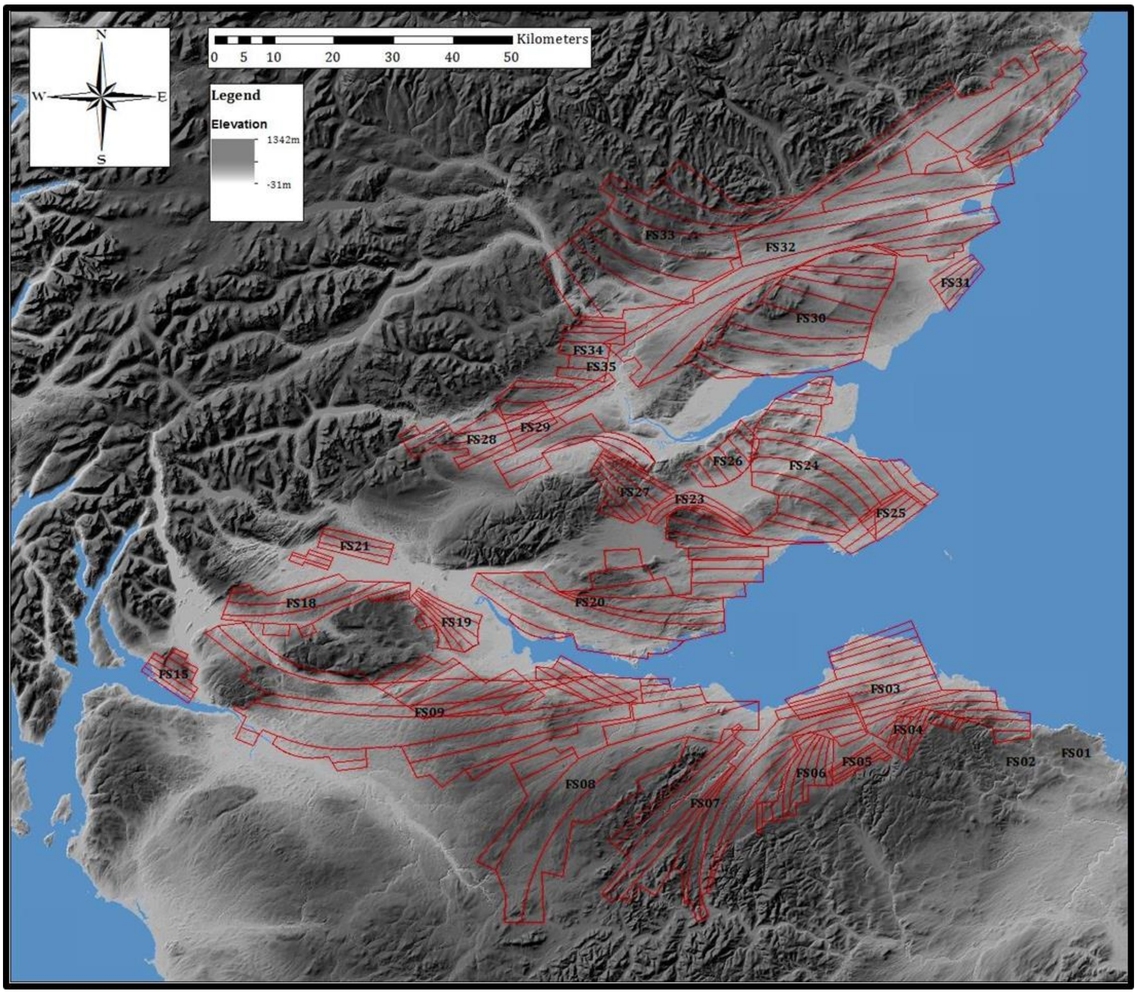

Figure 6.7 - Flow sets in the study which show an overall divergent shape with some areas exhibiting local scale converging patterns. Ice appears to have converged in four areas towards the North Sea on the east coast (see fig 6.8).

There are however, different sub-catchment scale flow sets pointing to local flow convergence. Figure 6.7 shows the flow sets in the study area and it is clear to see the overall diverging pattern.

However, there are several flow-sets in the study area exhibiting converging patterns. Ice appears to have converged in four areas towards the North Sea on the east coast. In the north of the study area there are seven flow (FS28, FS29, FS30, FS31, FS32, FS33, FS34) sets converging in a north easterly direction. They flow over and around the Sidlaw Hills into the North Sea at Montrose and Stonehaven (Fig 6.8a, Fig 3.1). Six flow-sets (FS20, FS23, FS24, FS25, FS26, FS27) converge in an easterly direction in the east of the study area. They flow over and around the Ochil and Lomond Hills (Fig 6.8b, Fig 3.1). In the west of the study area, there are eight flow-sets (FS9, FS11, FS12, FS15, FS17, FS18, FS19, FS21) converging in an easterly direction. They flow around the Kilpatric Hills, Campsie Fells and the Fintry Hills entering the Forth at Edinburgh (Fig 6.8c, Fig 3.1). In the south of the study area, there are six flow-sets (FA3, FS4, FS5, FS6, FS7, FS8) converging in a north easterly direction. They flow around the Pentland and Lammermuir hills (Fig 6.8d, Fig 3.1). Neither of these convergence zones feed into a trunk that is visible in the study area. This is because the trunk zone was likely offshore in the North Sea.

Stokes and Clark (1999) suggested that palaeo-ice streams are characteristically greater than 150 km long and 20 km wide. The onshore print of the Forth ice stream measures over 180 km long and from 40 km at the narrowest point to 120 km at the widest point wide making it a large imprint (Fig 6.9) and comparable to ice streams that have been identified, e.g. in the Laurentide Ice Sheet (Margold *et al*., 2015). These dimensions are larger than some palaeo-ice streams identified in the British Ice Sheet: for example, the Tweed measures <65 km long and 20 km wide (Everest *et al*, 2005), the Minch measures 150 km long and 30-40 km wide (Stoker and Bradwell, 2005; Bradwell *et al*, 2007). Therefore, if the Forth area does represent an ice stream, it may be one of the largest ice streams identified from the British ice sheet, apart from the Irish Sea ice stream which is much larger, and comparable in size with the Irish Sea ice stream and ice steams identified from the Laurentide ice sheet, such as Des Moines Lobe, Minnesota which is 900 km long and 200 km wide (Patterson, 1997).

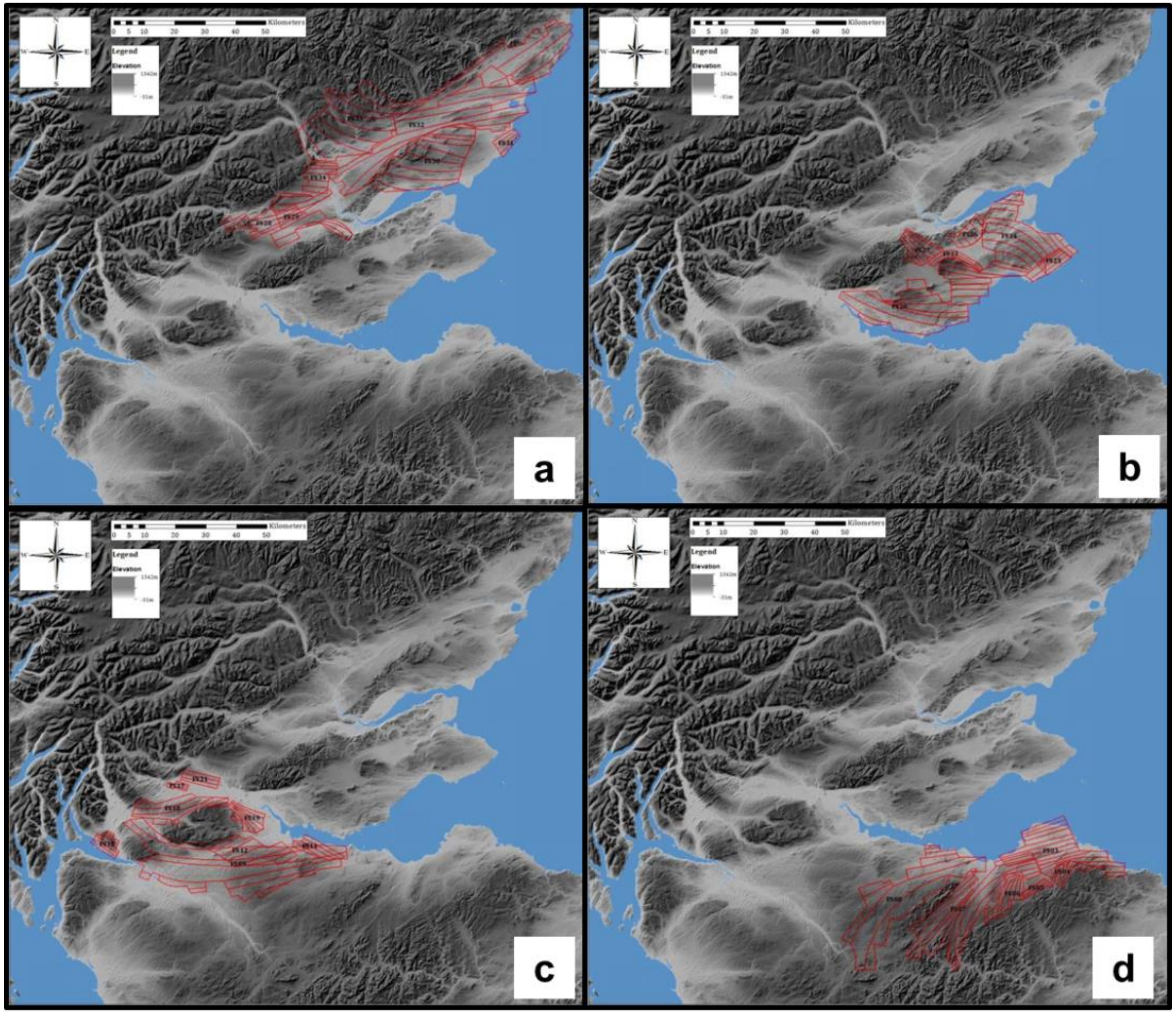

Figure 6.8 - a) This shows the flow sets in the north of the study area converging in a north easterly direction. They flow over and around the Sidlaw Hills into the North Sea at Montrose and Stonehaven. b) This shows six flow sets converging in an easterly direction in the east of the study area. They flow over and around the Ochil and Lomond Hills. c) In the west of the study area, there are eight flow sets converging in an easterly direction. They flow around the Kilpatric Hills, Campsie Fells and the Fintry Hills entering the Forth at Edinburgh. d) In the south of the study area, there are six flow sets converging in a north easterly direction. They flow around the Pentland and Lammermuir hills.

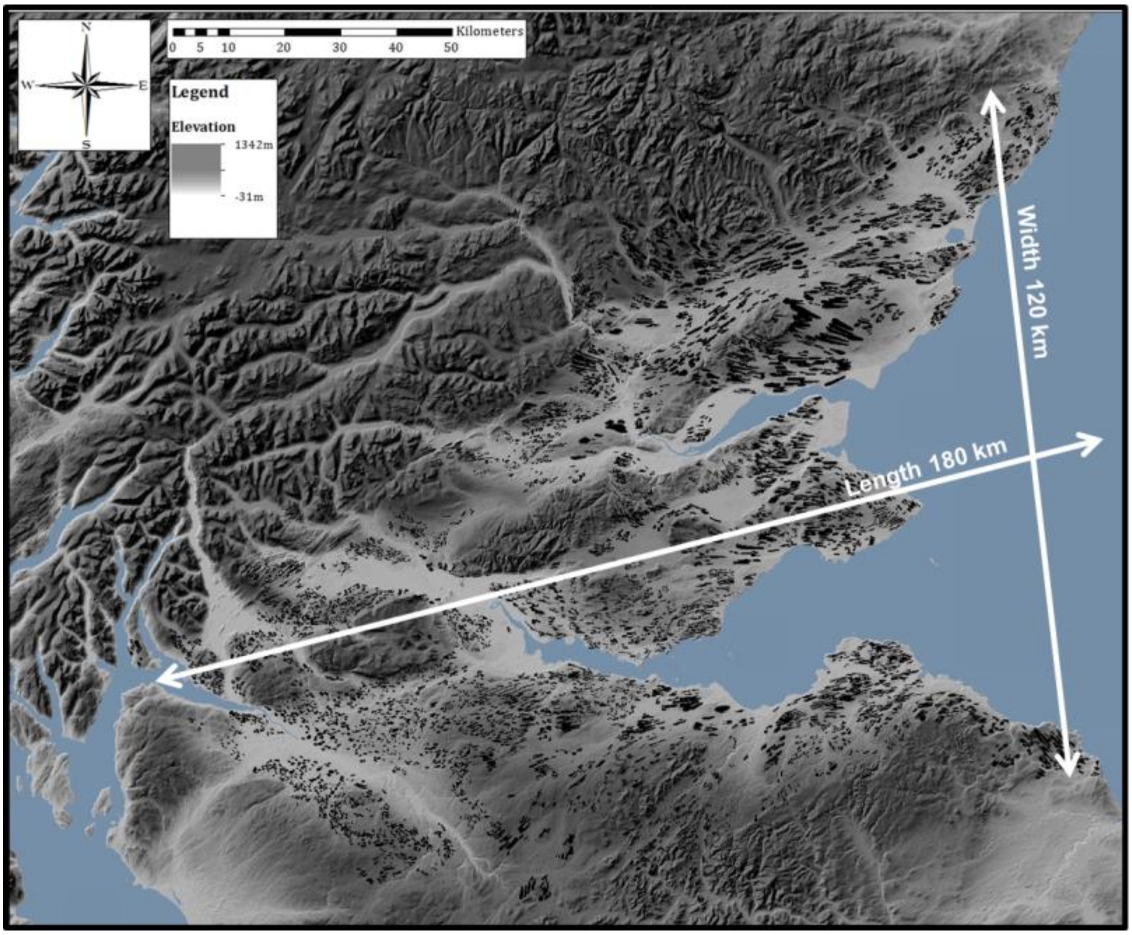

Figure 6.9 - This shows the sixe and shape of the ice stream as well as clear evidence of abrupt lateral margins in the study area that appears to be controlled by the topography of the area.

6.3.2 Sharply delineated margin and focused sediment delivery

Stokes and Clark (2002) proposed that a sharply delineated shear margin is characterised by abrupt lateral margins and the presence of ice stream shear margin moraines. It is expected that at the margin of palaeo-ice stream beds, there will be a distinct change in landforms reflecting a sharp lateral gradient in the velocity of the ice movement. The difference in the velocity of ice stream flow and ice bordering the ice stream is said to be a minimum of an order of magnitude (Stokes and Clark, 2001). Modern ice streams exhibit crevassed zones which represent the transition from high- to low- velocity ice flow. There is clear evidence of abrupt lateral margins in the study area that appears to be controlled by the topography of the area. Figure 6.9 shows all of the landforms mapped in the study area and the abrupt margins can be seen where the landforms stop. This is where higher ground is. The northern margin of the ice stream is delineated around the highland boundary fault by the Grampian mountains (Fig 6.9, Fig 3.1). The Lammamuir Hills and the Pentland Hills form the southern margin of the ice stream (Fig 6.9, 3.1). This strongly suggests that the Forth imprint is topographically controlled, even though abrupt shear margins are less obvious.

The presence of shear margin moraines at the side of drumlin fields also indicates a sharply delineated margin. These landforms are narrower and lower that drumlins and are often characterised by a single ridge of drift (Stokes and Clark, 2002). No shear margin moraines were identified in the study area, either in this study or by Hughes (2010). However, numerous other palaeo-ice streams do not show evidence of these landforms (Everest *et al*., 2005) and their presence has only been documented in selected locations (Dyke and Morris, 1988), which might suggest that the conditions required to form these features are quite rate (cf. Hindmarsh and Stokes, 2008).

Another indication of ice stream activity is a focused build-up of sediment on continental shelves (Vorren and Laberg, 1997). However, as this research is focused on the onshore print of the Firth of Forth area, any evidence of this has not yet been investigated. Off shore data would complement the work completed in this study and hugely strengthen the evidence of ice streaming that has been found.

6.3.3 Rapid velocity

On soft bedded ice streams, a rapid velocity is inferred from highly attenuated bedforms and boothia-type erratic dispersal trains (Dyke and Morris, 1988). Boothia type-erratic dispersal trains have not been identified in the study area; however, there is not necessarily a connection between ice stream activity and these dispersal trains, which are quite rare (Clark and Stokes, 2005). Moreover, any form of sediment dispersal and till geochemical analysis was beyond the scope of this project.

Streamlined bedforms are an indication of ice movement. Highly attenuated drift bedforms such as drumlins can be formed in one of two ways. They may be a product of slow moving ice over a long period of time or fast ice flow over short time periods (Clark, 1994). It is more widely accepted that streamlined forms develop as a result of fast ice flow over short periods. Hart (1999) and Stokes and Clark (2002) observed distinct differences in bedform attenuation within and outside ice stream margins. Bedforms in ice stream tracks were more attenuated than those outside the tracks. If it were true that attenuation resulted from slow ice movement over long time periods, the bedform attenuation would have been the same across the whole ice sheet. Many palaeo-ice streams have been identified from locations displaying swarms of highly attenuated bedforms which record the flow direction as well as the spatial extent of the ice streams (Everest *et al.*, 2005; Stoker and Bradwell, 2005).

The extent of bedform attenuation is quantified using elongation ratio. Many studies have connected high elongation ratios and inferred fast ice flow and streaming activity (Stokes and Clark, 1999; Stokes and Clark, 2003; Clark and Stokes, 2005; Everest *et al.*, 2005; Bradwell *et al.*, 2007;). Stokes and Clark

(1999) suggested that bedform elongation ratios of >10:1 suggest past ice streaming activity. The elongation ratios of the drumlins identified on the bed of the Forth area range from 1:1 to 11:1 with a mean of 3:1. Although the elongation ratios of the bedforms are not as high as Stokes and Clark (1999) suggested for ice streaming, patterns in length and elongation can be identified. Moreover, most papers report extreme maximum values and average values are often much lower (Spagnolo *et al*., 2014). Figures 6.10 and 6.11 show the average length and elongation ratio of drumlins found within each of the flow-sets identified in the Forth area. The larger flow-sets appear to have longer and more elongate bedforms. Eleven flow-sets (FS1, FS2, FS3, FS8, FS23, FS24, FS27, FS30, FS31, FS32, FS33) contain drumlins with particularly long lengths.

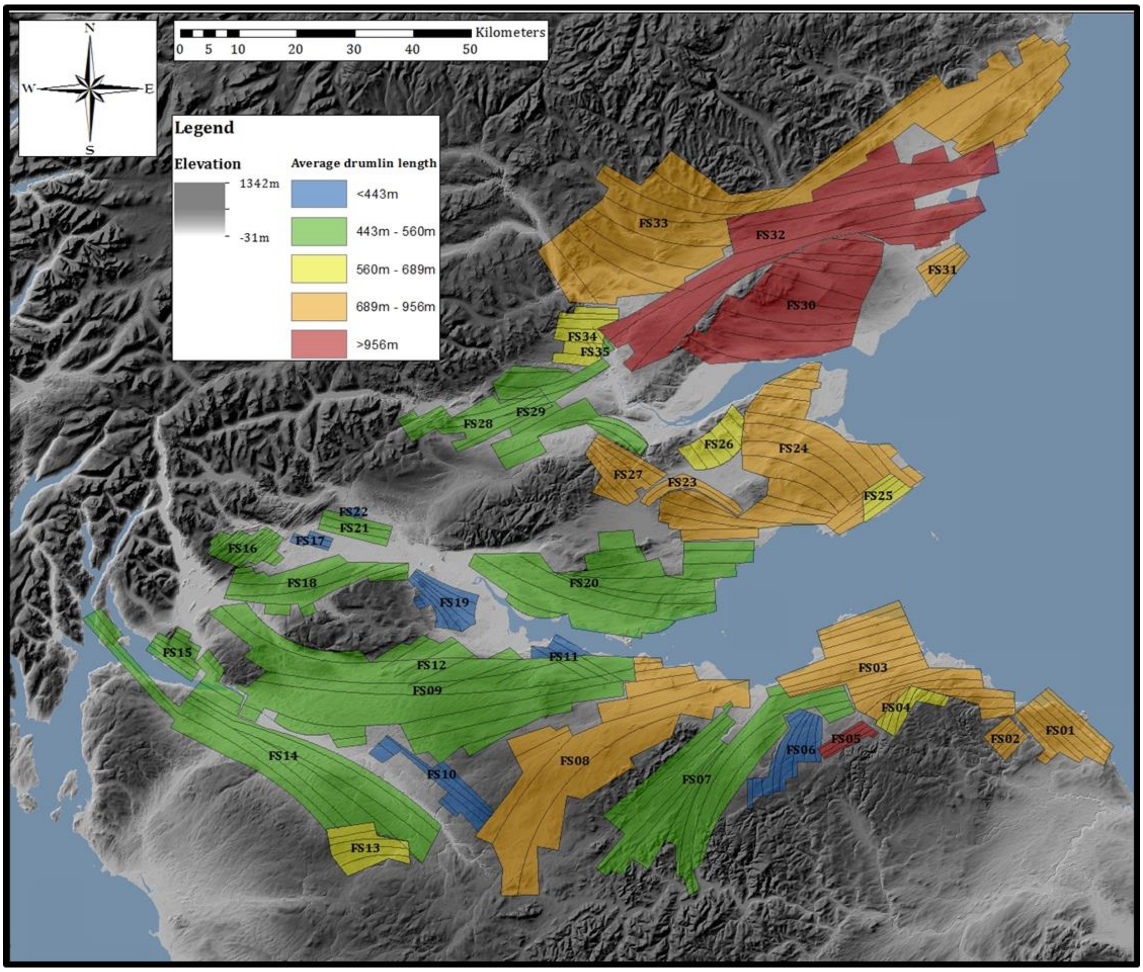

Figure 6.10 - This shows the average length of drumlins found within each of the flow sets identified in the Forth ice stream. The larger flow sets appear to have longer bedforms.

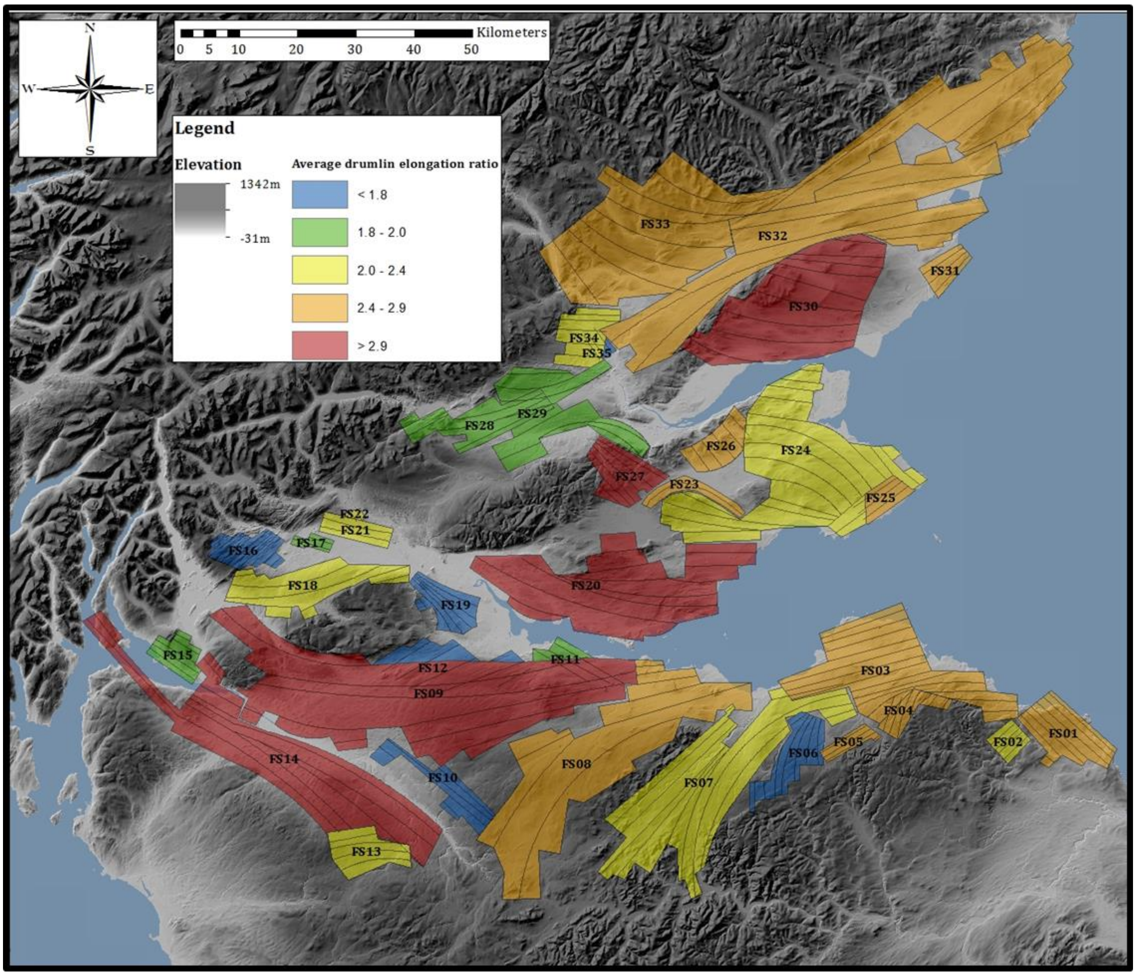

Figure 6.11 - This shows the average elongation ratios of drumlins found within each of the flow sets identified in the Forth ice stream. The larger flow sets appear to have more elongate bedforms.

Clark and Stokes (2005) also suggested that there are expected patterns of elongation ratio within ice streams. They suggested that bedforms are more elongate in the trunk as opposed to the converging onset zone. They also suggested that bedforms are more elongate along the central axis of the trunk. Furthermore, for marine terminating ice streams, they suggested that elongation ratios should steadily increase towards the grounding line. The evidence for this distinct velocity pattern is discussed in the following section

6.3.4 Distinct velocity pattern

Although the bedforms identified in the Forth area do not have particularly high elongation ratios, this does not necessarily mean that it is not a palaeo-ice stream. As suggested earlier, the onshore print of the Forth appears to be the onset zone of an ice stream, feeding a trunk which stretches out into the North Sea. It is therefore to be expected that onset zone bedforms have lower elongation ratios than those found in the trunk.

The spatial pattern of bedform elongation ratios within the onset zone may also be suggestive of ice stream activity. Ice streams display a characteristic known as plug flow (Clark and Stokes, 2005). This term combines two features; ice increasing in speed from onset to termination (in marine-terminating ice streams) and ice having a higher velocity in the centre of the stream, slowly decreasing towards the margins before exhibiting a sharp decrease in velocity. Figures 6.11 and 6.13 shows the drumlins identified in the Forth ice stream coloured according to length and elongation ratio. These images shows a clear pattern of drumlin length and elongation ratio increasing from the ice stream onset to the end of the onshore print. This is particularly evident in the north east flow pattern (Strathmore) where drumlin length and elongation increase from the local converging onset to the end of the onshore print.

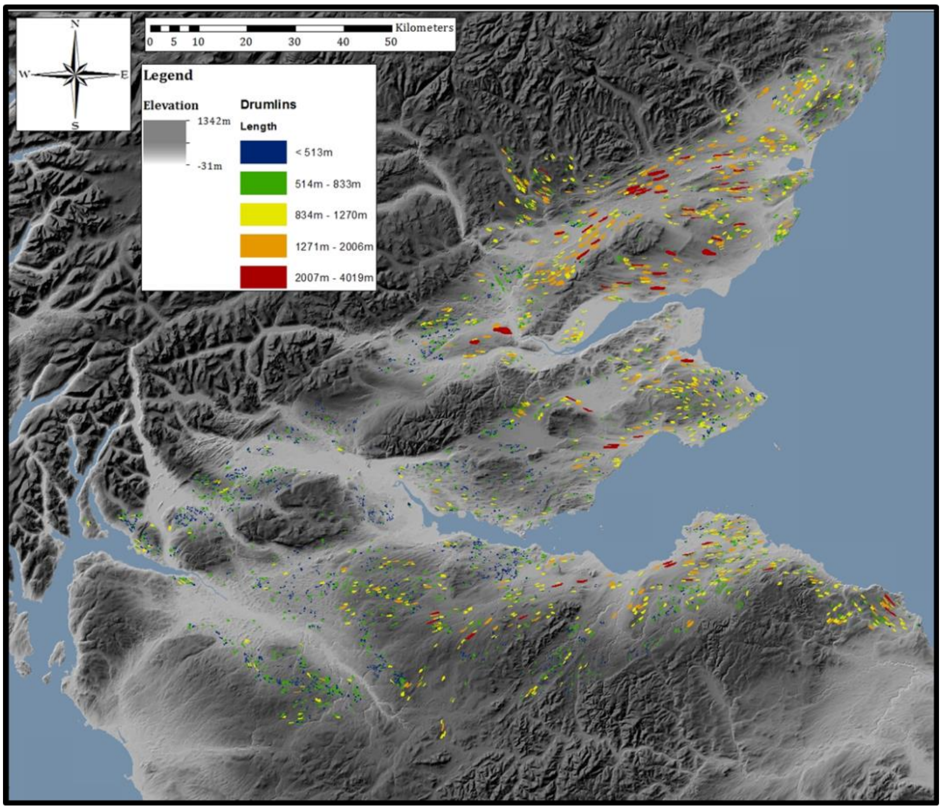

Figure 6.12 - This shows the drumlins identified in the Forth ice stream coloured according to length. This image shows a clear pattern of drumlin length increasing from the ice stream onset to the end of the onshore print. This is indicative of a marine terminating ice stream.

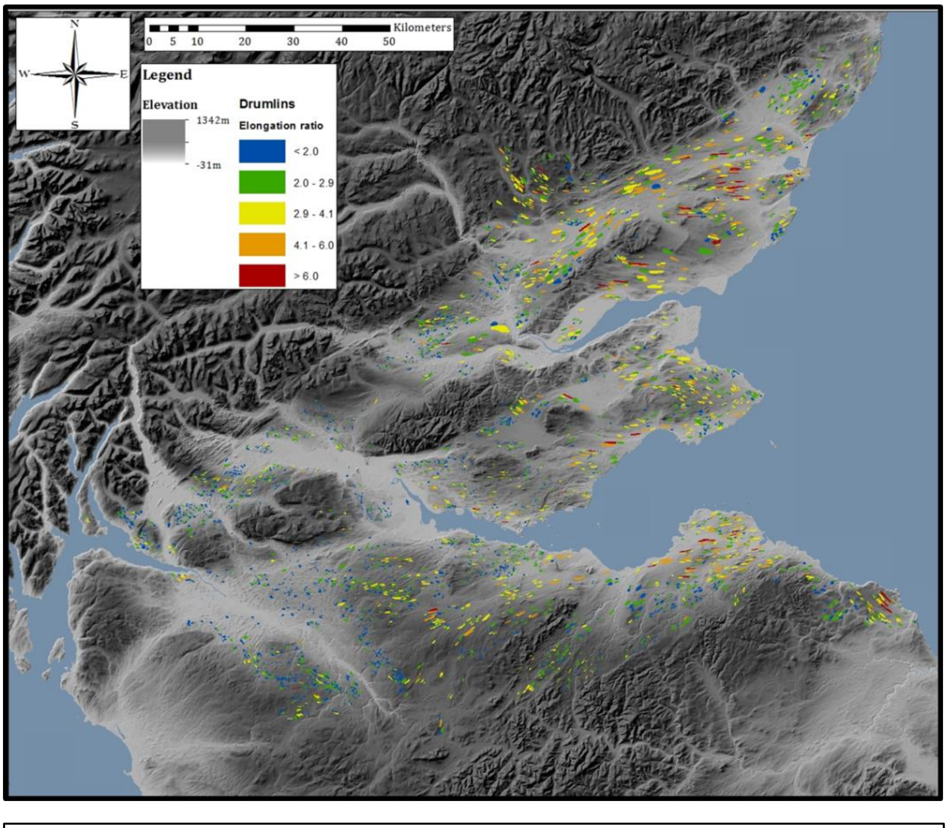

Figure 6.13 - This shows the drumlins identified in the Forth ice stream coloured according to elongation ratio. This image shows a clear pattern of drumlin elongation increasing from the ice stream onset to the end of the onshore print. This is indicative of a marine terminating ice stream.

6.3.5 Bedrock forms

The bedrock forms identified in the study area were classed as streamlined bedrock ridges, crag-and-tails and intermediate forms. Crag-and-tails are useful recorders of ice direction. As they are hybrid, soft and hard bedforms, the soft part give information about the late phase or final flow event. They are formed by the removal of softer rock around a hard, volcanic crag. This hard rock acts as a barrier and a tail of softer rock or drift is formed down ice. Fig 6.14 shows the length of the crag-and-tails identified in the study area. It is clear that the crag-and-tails are found in groups of similar length. The crag-and-tails are found in swarms and are mostly found in FS1, FS24, FS30 and FS33.

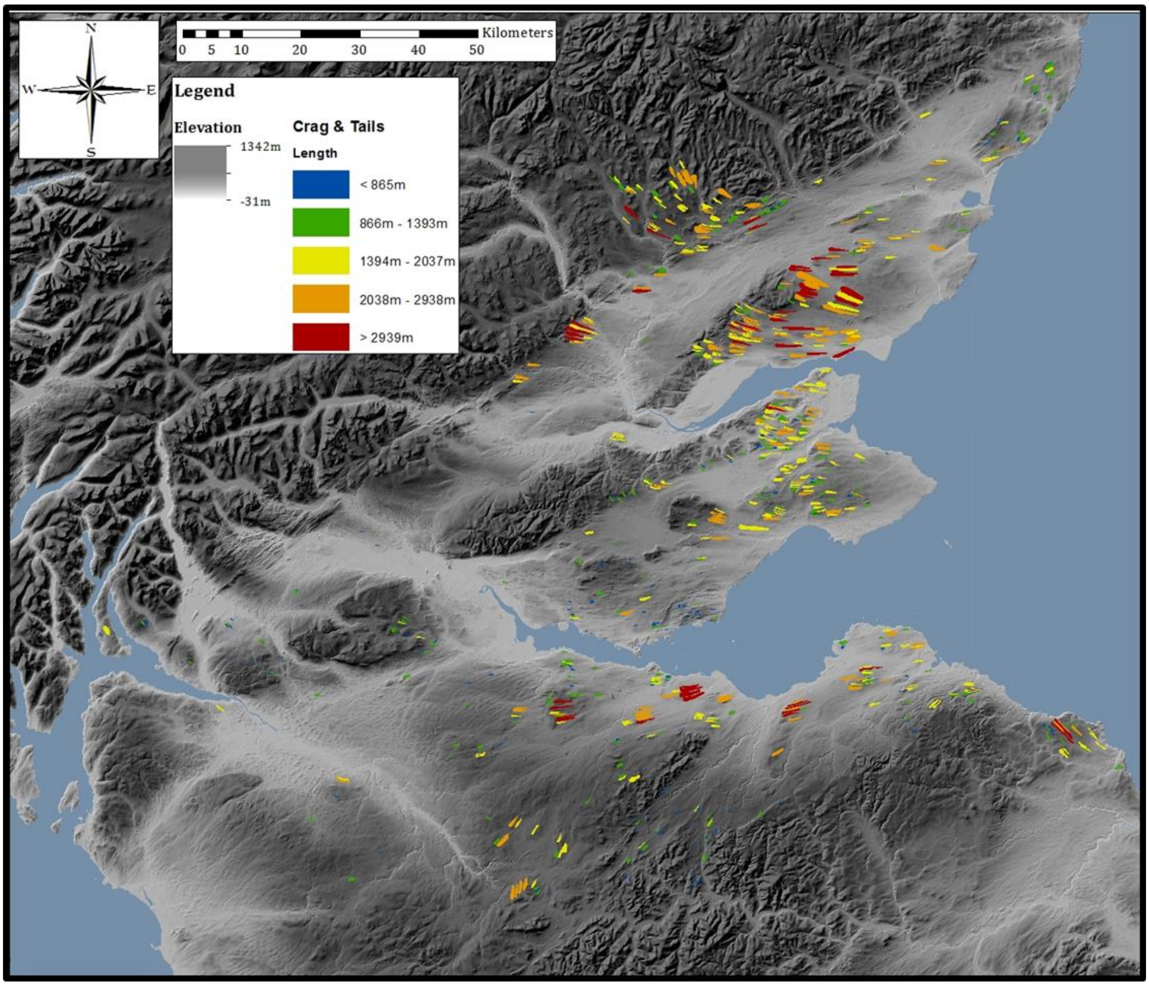

Figure 6.14 - This shows the length of the crag-and-tails identified in the study area. It is clear that the crag and tails are found in groups of similar length suggesting a fluctuation in the velocity of the ice stream over space and time.

The intermediate forms identified in the study area are similar in morphology to the ‘rock drumlins’ (bullet shaped bedrock landforms) identified by Eyles (2012). Bedrock forms exhibit a different morphology to drift forms under ice stream conditions. Lowe and Anderson (2002) noted a difference in geomorphology of streamlined bedforms on hard and soft sections of the Pine Island Bay ice stream. They found that thick ice was flowing slowly over bedrock and was influenced by significant amounts of meltwater. Thinner ice that was flowing more rapidly was grounded on a sedimentary substrate. Roberts and Long (2005) also noted bedrock bedforms with elongation ratios of <5:1. Figures 6.15 and 6.16 show the length and elongation ratios of the intermediate forms identified in the Forth area. The elongation ratios of the intermediate forms are very small, most between 1:1 and 2:1. The forms with slightly higher elongation ratios (3:1 – 6:1) do not appear to follow any particular pattern and are dotted around the area, but the longer forms are generally located towards the east. Figures 6.17 and 6.18 show the average length and elongation ratio of intermediate forms found within each of the flow-sets identified in the Forth ice stream. This is very similar to the average length and elongation ratio of drumlins within each flow-set.

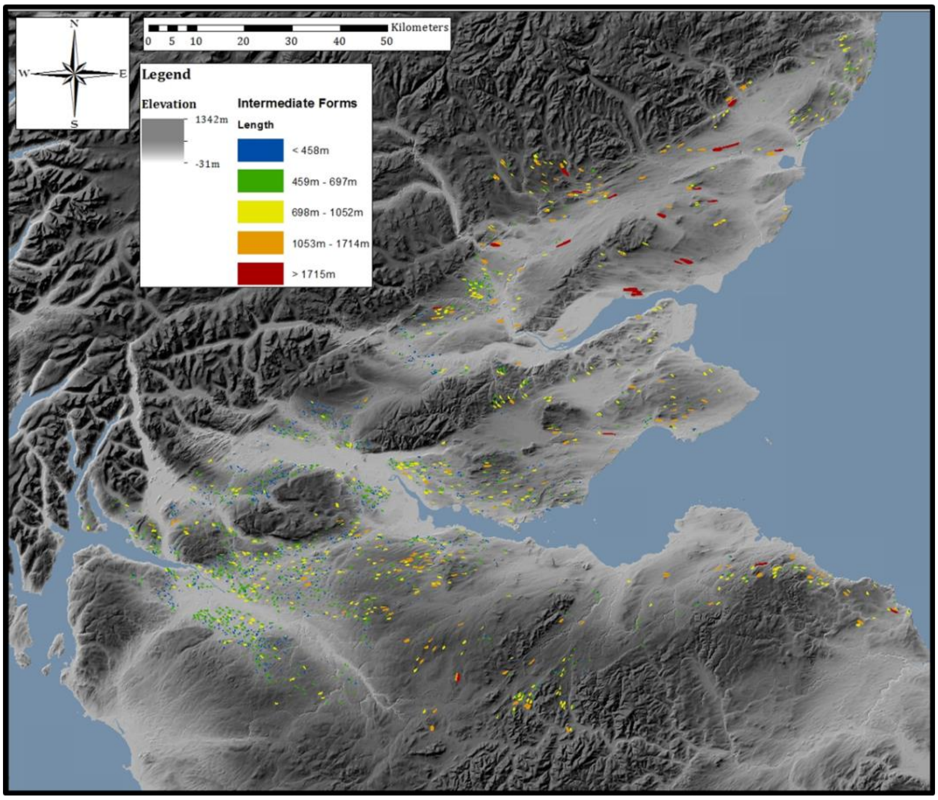

Figure 6.15 - This shows the intermediate forms identified in the Forth ice stream coloured according to length.

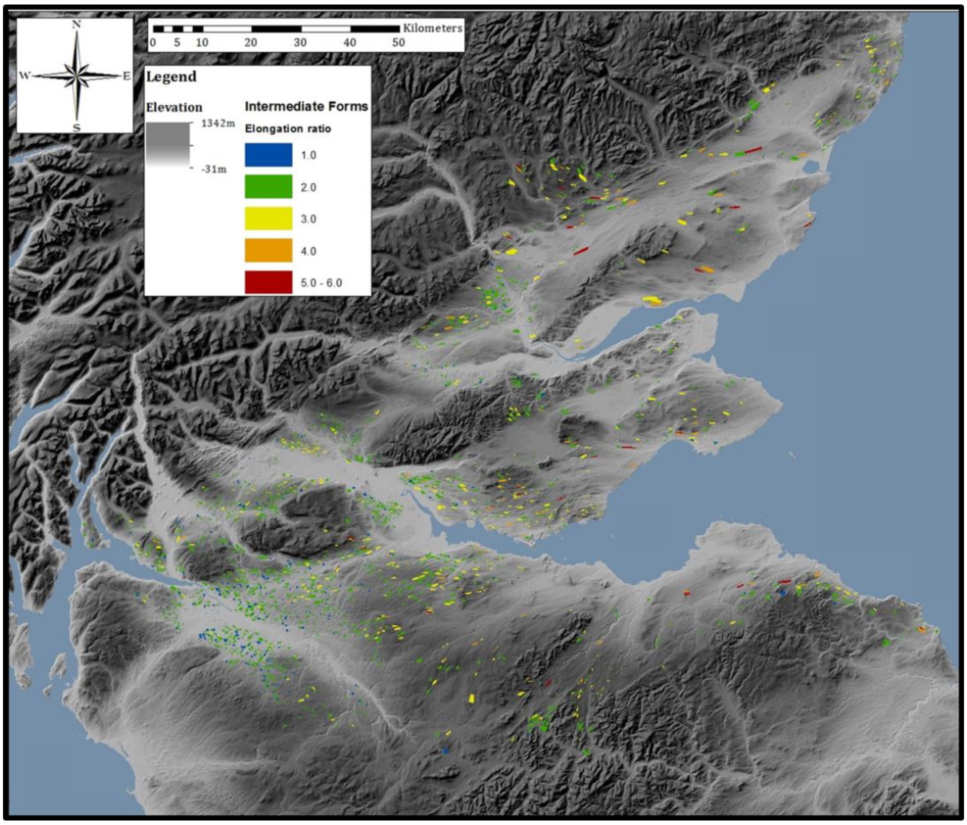

Figure 6.16 - This shows the intermediate forms identified in the Forth ice stream coloured according to elongation ratio.

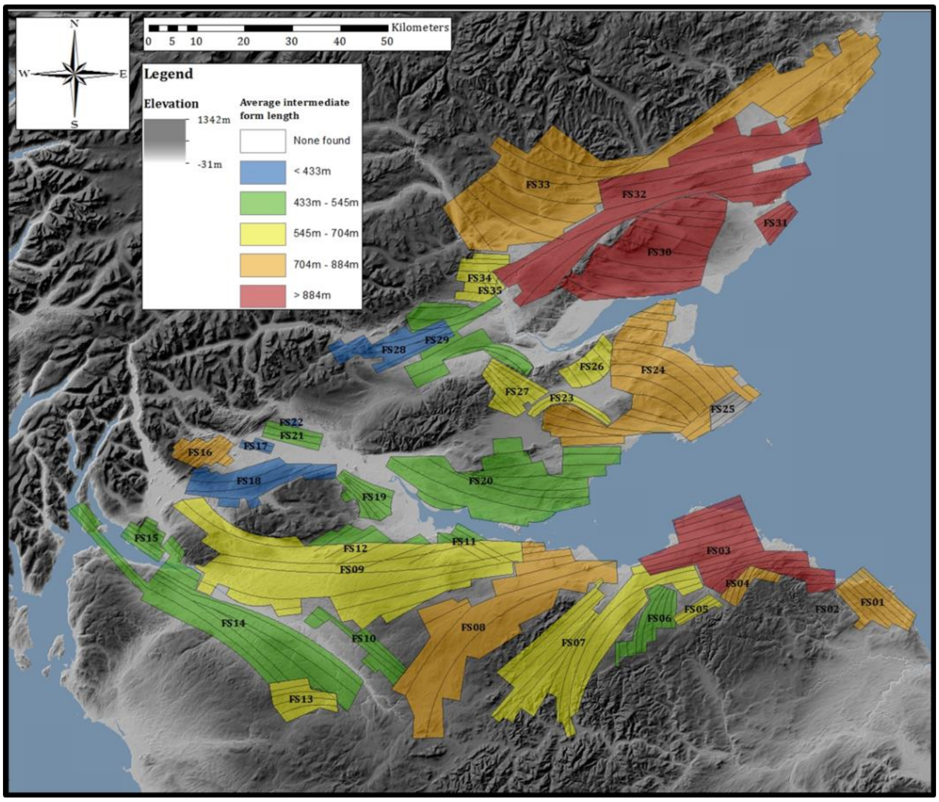

Figure 6.17 - This shows the average length of intermediate forms found within each of the flow sets identified in the Forth ice stream.

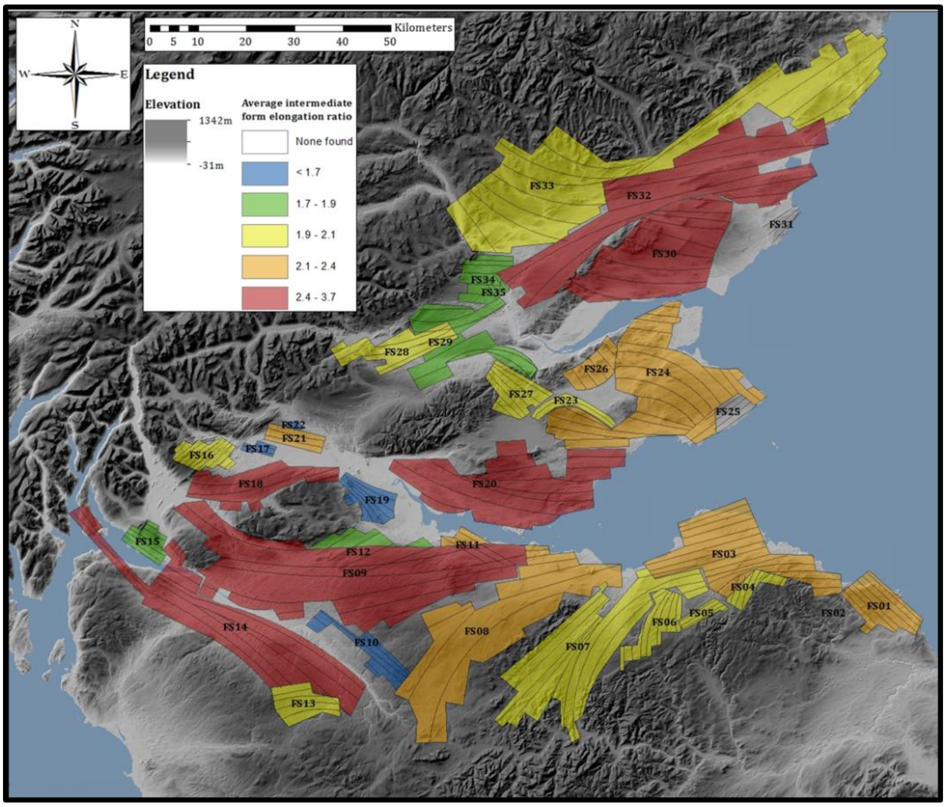

Figure 6.18 - This shows the average elongation ratios of intermediate forms found within each of the flow sets identified in the Forth ice

6.3.6 Summary

The evidence suggests that the Firth of Forth area is an onset zone of a palaeo-ice stream. The study area exhibits some of the features of a palaeo-ice stream signature. It has an overall divergent shape with local zones of convergence and large dimensions which are characteristic of an ice stream. It exhibits a sharply delineated margin bounded by topography, although shear lateral margin moraines were not found. There appears to be a distinct velocity pattern across the ice stream and there is some evidence of velocity increasing towards the east and along the ice stream. The bedrock forms also have some characteristics of ice stream bedforms (Table 6.1) in that they are characteristically similar in morphometry in size and shape to rock drumlins. The Forth has a mixed bed; with a mosaic of different bedforms influenced heavily by topography, bedrock outcrop and bedrock type. The onset zone is a complicated shape because of the north east flow (Strathmore) and south east flow which displays an overall divergent shape. However, flow set mapping does suggest convergence of specific areas during several phases.

Table 6.1 - A summary of how each of the ice stream criteria are met in the study area.

Characteristic shape and dimensions	• North of study area – 7 flow sets converge in a north easterly direction (FS28, FS29, FS30, FS31, FS32, FS33, FS34) • East of study area – 6 flow sets converge in an easterly direction (FS20, FS23, FS24, FS25, FS26, FS27) • West of study area – 8 flow sets converge in an easterly direction (FS9, FS11, FS12, FS15, FS17, FS18, FS19, FS21) • South of study area – 6 flow sets converge in a north easterly direction (FS3, FS4, FS5, FS6, FS7, FS8)	**Fig 6.7** **Fig 6.8** **Fig 6.3**

Sharply delineated margin	• Clear evidence of abrupt lateral margins in the study area • Controlled by the topography of the area • Northern margin - delineated around the highland boundary fault by the Grampian mountains • Southern margin – delineated by the Lammamuir Hills and the Pentland Hills.	**Fig 6.9**
Focused sediment delivery	Not found	
Rapid velocity	• 11 flow sets have drumlins with the longest average length (FS1, FS2, FS3, FS8, FS23, FS24, FS27, FS30, FS31, FS32, FS33) • 16 flow sets with the highest average elongation ratios of drumlins (FS1, FS3, FS4, FS5, FS8, FS8, FS14, FS20, FS23, FS25, FS26, FS27, FS30, FS31, FS32, FS33)	**Fig 6.10** **Fig 6.11**
Distinct velocity pattern	• Clear plug flow pattern of drumlin length and elongation ratio increasing from the ice stream onset to the end of the onshore print	**Fig 6.12** **Fig 6.13**
Bedrock Forms	• The crag and tails are found in swarms across 4 flow sets (FS1, FS24, FS30, FS33) • 9 flow sets with the longest average length of intermediate forms (FS1, FS3, FS4, FS8, FS16, FS24, FS30, FS31, FS32)	**Fig 6.14** **Fig 6.15** **Fig 6.16** **Fig 6.17** **Fig 6.18**

6.4 Nature of ice stream imprint

There have been relatively few mixed bed ice streams identified and so the reconstruction of the Forth ice stream presented here will help to provide additional information on how geology controls bedform morphometry and type on mixed beds. There is no visible hard bed – soft bed transition in the study area. It is just a heterogeneous mixed bed, with no obvious spatial transitions or patterns. It is therefore concluded that the study area is a mixed hard/soft bed subglacial mosaic which sits upstream in the onset zone of an ice stream. This is very similar to the observations reported by Graham *et al*. (2009), who identified a complex arrangement of bedforms indicating a multi-temporal record of flow. They found that geology played a key role in the bedform imprint which was divided into rough bedrock and sedimentary strata.

Flow traces are found in clusters across the study area in low lying areas (Fig 5.2). They are small in number and are all found on softer rock with overlying drift. Drumlins occur all over the study area, but their numbers increase down ice, as does their density (Fig 5.4). They also become more elongate down ice towards the onshore/offshore transition. They tend to occur on softer rock with overlying drift. Intermediate forms occur all over the study area, but their pattern is the opposite of drumlins (Fig 5.6). Their numbers and density are higher up ice. Like drumlins, they also become more elongate down ice towards the onshore/offshore transition. Crag-and-tails are scattered throughout the study area and are found where the bedrock outcrops are (Fig 5.8). Streamlined bedrock ridges are found in clusters across the study area (Fig 5.10). They are small in number and are found on bedrock outcrops only where no overlying drift is evident.

There are no smooth transitions from one bedform type to another and the bedform patterns appear to be dependent upon the underlying geology. Graham *et al*. (2009), following their study of a West Antarctic palaeo-ice stream, also concluded that the bedforms patterns they identified were dependent on the subglacial substrate. As there are no landsystems models to represent a mixed bed palaeo ice stream, a simplified cartoon has been produced to characterise this mixed bed palaeo-ice stream onset zone (Fig 6.19). Fig 6.19 is an idealised and simplified schematic landsystem of a topographically-controlled onset zone of a mixed bed palaeo-ice stream. Flutes are found in clusters, down ice away from bedrock outcrops. Drumlins are found in clusters across the whole onset zone but concentrated down ice away from bedrock outcrops. Rock drumlins are found in clusters across the ice stream but concentrated up ice, away from large bedrock outcrops. Crag-and-tails are found on bedrock outcrops. Bedrock ridges are found on bedrock outcrops and at the margins of the ice stream on bedrock. It is expected that other landforms such as rouches moutonnées, whalebacks, and lateral moraines may also be found in a mixed bed landsystem. More streamlined landforms such as MSGLs, megaflutes and megaridges will most likely be found in the trunk of this type of landsystem, and we predict they will occur offshore to the east of our study area further downstream.

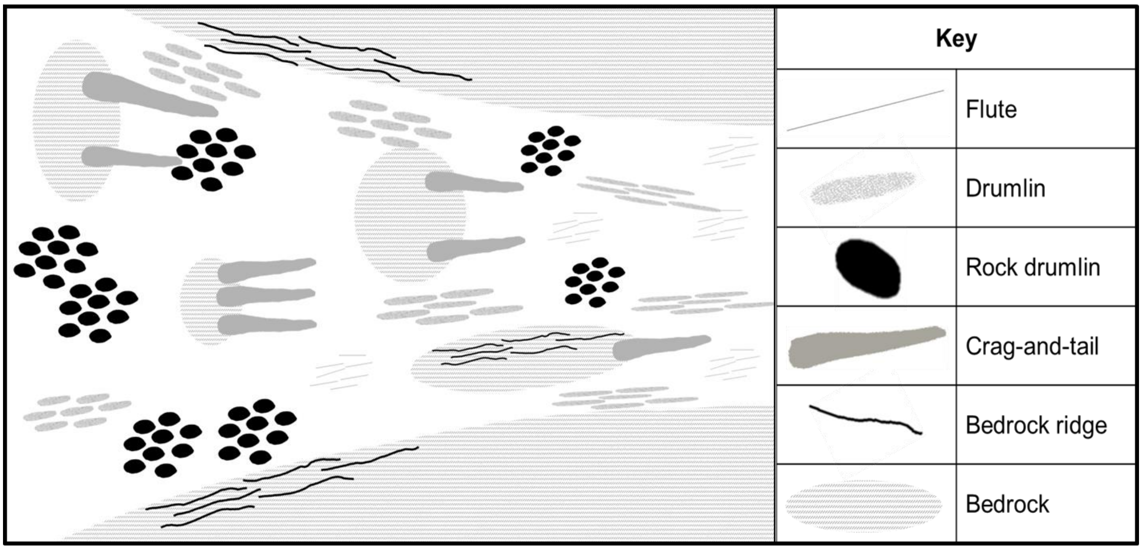

Figure 6.19 - This shows a cartoon landsystem of a tomographically controlled onset zone of a mixed bed palaeo-ice stream. Flutes are found in clusters, down ice away from bedrock outcrops. Drumlins are found in clusters across the whole onset zone but concentrated down ice away from bedrock outcrops. Rock drumlins are found in clusters across the ice stream but concentrated up ice, away from large bedrock outcrops. Crag and tails are found on bedrock outcrops. Bedrock ridges are found on bedrock outcrops and at the margins of the ice stream on bedrock.

Chapter 7 – Conclusions

The overall aim of this study was to determine if the Firth of Forth area exhibits glacial geomorphological evidence of palaeo-ice stream activity. This was achieved through a variety of ways. First, an examination and characterisation of the glacial geomorphology of the Forth region was undertaken using remote sensing. Over 10,000 landforms were digitally mapped and categorised. This data was then analysed using established criteria to test whether the Firth of Forth was the location of an ice stream. The landforms and subglacial landsystem were examined and the relative influences of bedrock geology and topography on the ice stream imprint were determined. Finally, a reconstruction of the chronology and glacial history of the Forth area was produced and this was used to gain an understanding of the influence that the ice stream had on regional ice sheet history.

The key findings of this investigation are as follows:

- The Firth of Forth area was once an ice stream operating in the British Ice Sheet.
- The imprint in the study area measures at least 180 km long by 120 km wide which fits the expected size of an ice stream
- The Forth ice stream has abrupt lateral margins governed by topography.
- There is evidence of elongate bedforms (elongation rations > 10:1) suggesting fast ice flow and streaming activity.

- The locations of the bedforms found in the study area are dependent on the underlying geology and topography, with many bedforms found converging between areas of high ground.
- The study area represents a mixed-bed onset zone of the Forth ice stream hypothetically feeding into a trunk zone in the North Sea.
- The orientation of the bedforms suggest that the ice stream split into two during deglaciation as it became topographically constrained, one which flows north east and the other which flows south east.
- The forth ice stream operated around 19 ka – 15 ka

The identification of the Firth of Forth ice stream supports previous modelling that an ice stream existed here. It also provides a useful observational template to help identify other mixed bed ice streams. It would be a useful site to test patterns and rates of deglaciation if future work could date the ice stream retreat.

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